Modification of starch

Fan, Yifei; Picchioni, Francesco

Published in:
Carbohydrate Polymers

DOI:
10.1016/j.carbpol.2020.116350

Publication date:
2020

Carbohydrate Polymers 241 (2020) 116350

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Review

Modification of starch: A review on the application of "green" solvents and controlled functionalization

Yifei Fan, Francesco Picchioni*

Engineering and Technology Institute Groningen, University of Groningen, Nijenborgh 4, 9747AG Groningen, the Netherlands

ARTICLE INFO

Keywords:
Starch
Ionic liquids
Supercritical CO_2
Regioselective
Controlled grafting

ABSTRACT

Starch is a polysaccharide widely present in nature and characterized by a wide range of applications. This often implies the necessity for various novel properties with respect to those of native starch, mainly achievable via chemical modification. During the last decades, products with new or enhanced properties were prepared from starch because of the adoption of "green" solvents (ionic liquids and supercritical CO_2) and several new techniques (regioselective derivatization, atom transfer radical polymerization, etc.) that are characterized by controlled modification. However, reviews on these works seem very rare. In this article, the application of ionic liquids and supercritical CO_2 in the modification and processing of starch is summarized. The development of regioselective derivatization and controlled grafting of starch are also reviewed in the second part of this article.

1. Introduction

Starch, as the most abundant natural occurrence of polysaccharides that is just second to cellulose, widely exists in the roots, seeds, leaves of various plants, and some algae. Typically, starch granules are composed of two main fractions: amylose, a kind of linear polymer of glucose unit with α-(1→4) linkage and amylopectin, which is highly branched with lots of short chains that linked through α-(1→6) linkage to the linear parts of the macromolecule (Wu, Witt, & Gilbert, 2013). The difference in structure renders these two components differ significantly with each other in both physical and chemical properties. For example, amylopectin is easier to dissolve in hot water than amylose. Another significant difference is that only amylose could complex with iodine and make their solution appear blue-black color (Fig. 1).

People have made use of starches from various botanical resources for thousands of years and its application in modern industrial products has also been developed for many years. This is often related to its characteristic properties such as biodegradability, renewability, and cheapness. For instance, varieties of derivatives have been made from starch to oil drilling additives (Dias, Souza, & Lucas, 2015), for coatings/films (Lyytikainen et al., 2018; Saikia, Das, Ramteke, & Maji, 2017), adhesives (Nie, Tian, Liu, Wu, & Wang, 2013; Zhao, Peng, Wang, Wang, & Zhang, 2018), tissue engineering and drug carriers (Alfaifi, El-Newehy, Abdel-Halim, & Al-Deyab, 2014; Nakamatsu, Torres, Troncoso, Min-Lin, & Boccaccini, 2006; Zhang, Shan et al., 2013), biofuels (Ho, Ye, Hasunuma, Chang, & Kondo, 2014; Tanadul, VanderGheynst, Beckles, Powell, & Labavitch, 2014), etc.

Because of technological developments, the application field of starch is broadened progressively and different techniques have been developed for the modification of starch to overcome its shortcomings. These include poor processability and solubility in common organic solvents, retrogradation and syneresis, low shear stress resistance and thermal decomposition. Generally, there are four categories of methods for the modification of starch: physical, chemical, enzymatic and genetic engineering respectively (Ashogbon & Akintayo, 2014; Benavent-Gil & Rosell, 2017; Halley & Avérous, 2014; Lyytikainen et al., 2018; Masina et al., 2017). While the main purpose of genetic engineering is to modify the ratio of amylopectin to amylose and their structures for specific applications, physical modifications are employed to improve the granule size and solubility of starch in water. The applications of physical and biotechnological methods in the modification of starches have been kindly reviewed by Ashogbon et al. and Halley et al. respectively (Ashogbon & Akintayo, 2014; Halley & Avérous, 2014).

Compared with physical and genetic engineering modifications, chemical methods provide more options for the functionalization of starch and therefore broaden the application field significantly, especially with the help of new emerging chemical techniques. As is known, there are three hydroxyl groups adjacent to the carbon atoms at 2, 3 and 6 positions in each anhydroglucose unit (AGU), which enable the modification of the starch could be easily achieved through the chemical reaction with various functional groups. Traditional chemical modifications, including esterification and etherification, cationization,

* Corresponding author.
E-mail address: f.picchioni@rug.nl (F. Picchioni).

https://doi.org/10.1016/j.carbpol.2020.116350
Received 30 January 2020; Received in revised form 16 April 2020; Accepted 18 April 2020
Available online 29 April 2020

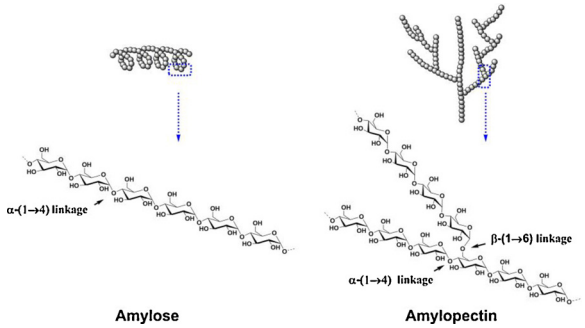


Fig. 1. Illustration of the structure of amylose and amylopectin.

oxidation as well as crosslinking, are usually realized through the reaction of starch with small molecules. These derivatives are widely used in the food industry and as additives for medicine, cosmetics, coatings, oil exploiting fluids and so on. The synthesis and applications of these kinds of derivatives have been reviewed in many papers published in recent years (Ashogbon & Akintayo, 2014; Chen et al., 2015; Masina et al., 2017). In the present work, we mainly focus on the newly emerging green solvent for modification and the progress of controlled modification of starch.

1.1. "Green" solvents for starch modification

Because of the intra-/inter-molecular hydrogen bonds between the hydroxyl groups along the backbone of the molecules, starch has a poor solubility in water and most common organic solvents. The modification of starch in aqueous solutions, in most cases, is carried out in a heterogeneous way, which, together with many other side reactions, limits the degree of substitution (DS) and the further application of these derivatives (Gao, Luo, & Luo, 2012). To get a higher DS, starch is dissolved and modified in some organic solvents with the help of some catalysts. Solvents and catalysts such as dimethyl sulfoxide (DMSO) and pyridine, however, are flammable, toxic and therefore hazardous towards both human and environment. With increasing attention being paid to health, safety and environment (HSE) protection, chemists are trying to find new solvents to displace traditional organic solvents for dissolving natural macromolecules and subsequent chemical reactions. In the past decades, the focus has been mainly paid to two kinds of "green" solvents, which are ionic liquids and supercritical carbon dioxide respectively, for the dissolution and modification of natural polysaccharides such as starch, cellulose, and chitin. The applications of these two solvents for starch are summarized below.

1.2. Ionic liquids

Ionic liquid (IL) usually is composed of a combination of organic cation and smaller organic or inorganic anion. With properties such as negligible volatility, non-flammability, thermal and chemical stability, tunable polarity and so on, IL attracted the attention of scientists who work on polymer science. Many reports on the successful application of various ionic liquids for different polymerization techniques, such as free radical and ionic polymerizations as well as controlled polymerizations (Chakraborty, Jähnichen, Komber, Basfar, & Voit, 2014; Vijayakrishna, Manojkumar, & Sivaramakrishna, 2015; Zhang & Zhu, 2015), have been made and reviews on this field are also available (Kubisa, 2009; Mota-Morales et al., 2018). Specifically, the application of ILs in the preparation of drug/gene delivery materials with biopolymers like starch has also been reviewed (Chen, Xie, Li, & Chen, 2018). In this present work, the applications, as well as limitations of ionic liquids as solvent and/or catalysts in the modification of starch, will be reviewed.

Various derivatizations of starches with ILs as solvents have been studied in recent years. For example, cationic corn starch was successfully synthesized by Wang and Xie et al. with 1-butyl-3-methylimidazolium chloride ([BMIM]Cl) as solvent (Wang & Xie, 2010). Glycidyltrimethylammonium chloride (GTAC) was used in their reaction for the derivatization of starch and a maximum DS of 0.99 was obtained. [BMIM]Cl was also used as a solvent for the esterification and carboxymethylation of starches. In the experiment carried out by Xie et al., corn starch was esterified with succinic anhydride and acetic anhydride with pyridine as the catalyst in [BMIM]Cl (Xie, Shao, & Liu, 2010). Succinylated starch with DS values that varied from 0.03 to 0.93 and acetylated starch with DS values ranged from 0.37 to 2.35 were successfully synthesized respectively. In another report, the carboxymethylation of corn starch in [BMIM]Cl was investigated and a maximum DS of 0.76 was obtained (Xie, Zhang, & Liu, 2011). Desalegn et al. also reported the synthesis of cassava starch epoxy fatty acid esters (starch vernolates) in which [BMIM]Cl was used as solvent and pyridine as catalyst (Desalegn, Garcia, Titman, Licence, & Chebude, 2014). A derivative with DS up to 1.03 was obtained within 24 h in their experiment. All these modifications were carried out in homogeneous conditions, thus had good control over the DS and the distribution of functional groups. In one more recent research, Zarski et al. reported the esterification of potato starch in [BMIM]Cl with immobilized lipase (from *Thermomyces lanuginosus*) as catalyst (Zarski, Ptak, Siemion, & Kapusniak, 2016). The highest DS obtained in their research was 0.22 when the reaction carried out at 60 °C for 4 h. The relative low DS compared with other reports was attributed to the incomplete dissolution of potato starch in [BMIM]Cl. This may be related to the relatively larger molecular weight of potato starch compared with starch from other resources (Bertoft & Blennow, 2016; Vanier, El Halal, Dias, & da Rosa Zavareze, 2017). Despite all these studies, however, systematic experimental comparisons of the effectiveness and efficiency of starch derivatization in ILs and other organic solvents (DMSO, *N,N*-dimethylacetamide (DMAc)/LiCl) are still not available.

Apart from the research mentioned above, the grafting of corn starch with *L*-Lactide by ring-opening graft polymerization (ROP) was also studied. In the report by Xu and Wang et al., 1-allyl-3-methylimidazolium chloride ([AMIM]Cl) was used as the reaction medium for the grafting of starch and the grafting efficiency of poly(*L*-lactide) (PLLA) was calculated to reach 30 % according to the standard curve based on FT-IR method (Xu, Wang, & Liu, 2008). Recently, Wang et al. also reported the synthesis of starch-based macroinitiator in [AMIM]Cl for the atom transfer radical polymerization (ATRP) grafting of polystyrene (PS) and poly(methyl methacrylate) (PMMA) (Wang, Yang et al., 2015). Corn starch was esterified with 2-bromoisobutyryl bromide in [AMIM]Cl at room temperature without using any additional catalysts. Compared with reactions carried out under heterogeneous conditions, the graft density and ratio were significantly improved with [AMIM]Cl as the solvent. Another IL used for the grafting of corn starch with PS was 1-ethyl-3-methylimidazolium acetate ([EMIM]Ac) (Men, Du, Shen, Wang, & Liu, 2015). In this report, PS was successfully grafted onto starch via conventional free radical polymerization. However, different from the one grafted via ATRP, the ratio between styrene and starch has a significant influence on the grafting percentage (GP), which is too high ratio (e.g. 3:1) will reduce the GP due to high monomer concentration. This is the inherent drawback of conventional free radical polymerization compared with controlled radical polymerization like ATRP.

Besides the application as solvent, several ILs, mainly 1-*N*-alkyl-3-methylimidazolium chlorides could also act as catalysts for the esterification of high-amylose maize starch (Lehmann & Volkert, 2011). In the research of Lehmann and Volkert, different carboxylic anhydrides were used as both reactants and solvents for the esterification of maize starch, while the amount of ILs was just kept to a low value. Imidazolium-based ILs with halogenides as counter ions were proved to be good catalysts for this reaction. They also found that the degradation of maize starch could be suppressed by the addition of pyridine or 1-

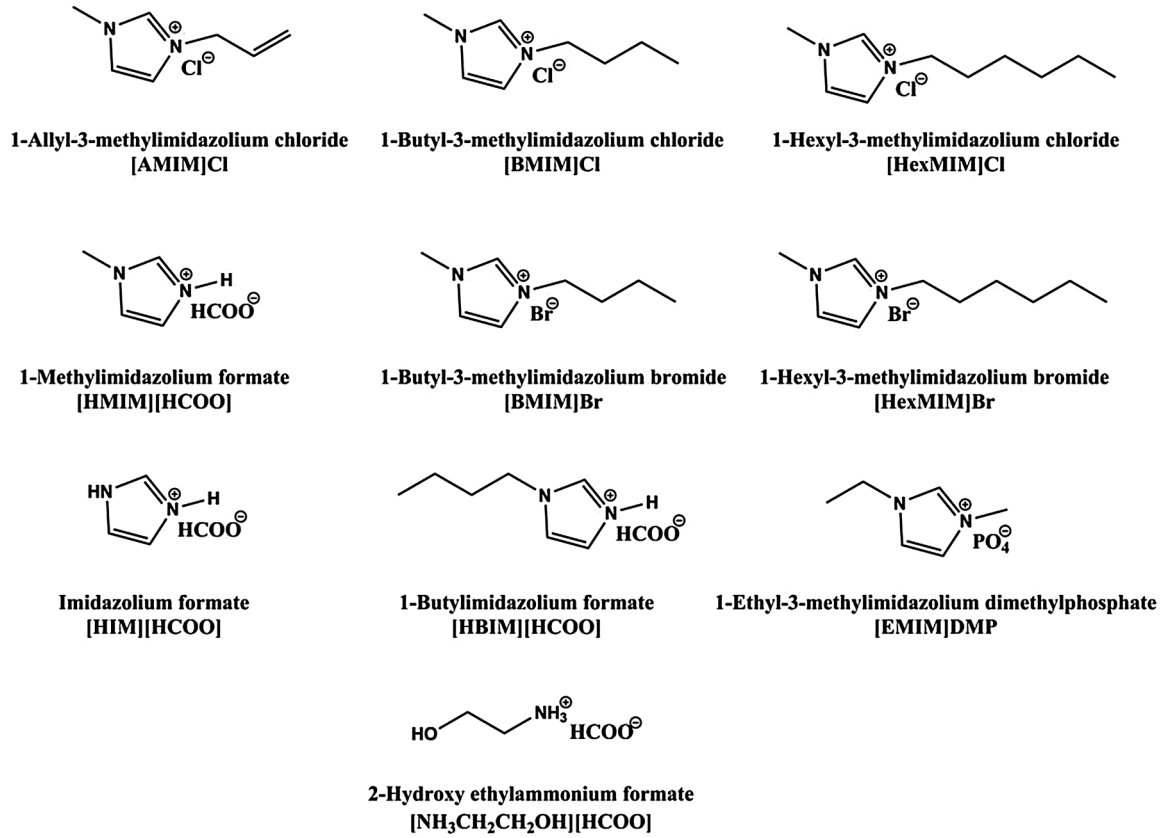


Fig. 2. ILs studied for the dissolution and depolymerization of barley starch (Lappalainen et al., 2013).

methylimidazole as the base and the average molar mass of starch acetate could be adjusted through varying the amount of pyridine added.

Concerning the dissolution and degradation of starch, it is of great importance to get a deep knowledge of the interactions between starch molecules and ILs for the successful modification of starch in ILs. Kärkkäinen et al. compared the dissolution and degradation of six different native starches (wheat, barley, potato, rice, corn, and waxy corn) in [BMIM]Cl under conventional oil bath heating and controlled microwave heating via liquid chromatography equipped with an evaporative light scattering detector (HPLC-ELSD). (Kärkkäinen, Lappalainen, Joensuu, & Lajunen, 2011). Results suggest that although a lower temperature (80 ˚C) was used in microwave heating compared with that of oil bath (100 ˚C), the dissolution and degradation process were both speeded up. Amylopectin was reported to degrade faster than amylose possibly due to its branched structure. A comparison between different starches showed that amylopectin with higher molecular weight degraded slower than that with smaller molecular weight. Similarly, Lappalainen et al. studied the dissolution and depolymerization of barley starch in ten ILs (Fig. 2) with *p*-TsOH as catalyst and microwave as the heating method (80 ˚C) (Lappalainen, Karkkainen, & Lajunen, 2013). It was found that barley starch could be depolymerized into 1000–2000 Da-sized, water-soluble oligomers by dialkylimidazolium halides that analyzed. Both cation and anion of the ILs were found to have significant influences on this dissolution process, to which a smaller cation or a more nucleophilic anion was proved to be more beneficial. This was related to the steric hindrance caused by the dialkylimidazolium cation and the ability of anion to break intra- and intermolecular hydrogen bonds of starch. In their research, $[NH_3CH_2CH_2OH][HCOO]$ and [EMIM]DMP were proved to be the most suitable solvent among those ten ILs for dissolving starch with a notable decreasing in depolymerization. According to the above-mentioned reports, although we cannot rule out the influence of heating on depolymerization of starch, the different degradation speeds of starch in various ILs do suggest the composition of ILs plays a vital role in the degradation process. One possible explanation is that the residual water in starch (and ILs) resulted in the formation of acid with the anion of ILs which catalyzed the depolymerization of starch (Kärkkäinen et al., 2011). As the molecular weight of starch significantly affects its application, further researches are needed to build up systematic guidance for us to choose the right ILs for the derivation of starch. Besides the influence of composition, the presence of water was also revealed to play a special role in dissolving starches. Liu and Budtova found that the dissolution of waxy corn starch in [EMIM]Ac could be accelerated with a proper amount of water ($\leq$ 50 *wt.*%) and no gelatinization was observed in this process (Liu & Budtova, 2013). Moreover, a decrease of about 20 ˚C in the beginning and final temperature of dissolution was noticed. A possible explanation for this is that the presence of water could induce the swell of starch granules which is favorable to the diffusion of [EMIM]Ac. Mateyawa and Xie et al. also studied the influence of water on the phase transition of maize starch (waxy and regular) in [EMIM]Ac (Mateyawa et al., 2013). They concluded that a higher water content ($>$ 25 %, mol ratio) could strengthen the interactions between [EMIM]Ac and water which reduced the available [EMIM]Ac for starch molecules, thus made gelatinization dominates the phase transition process of starch. With the decreasing of water content, more [EMIM]Ac became available and resulted in a conversion from gelatinization to dissolution for the phase transition process. However, a proper ratio (7.2 mol/mol) of water to [EMIM]Ac is required for the effective disruption of starch granules at a relative lower temperature (e.g., 40–60 ˚C), which is in accordance with the results from other reports (Liu & Budtova, 2013; Sciarini et al., 2015). In one recent report, the lowest temperature (28 ˚C), as far as we know, for the dissolution of maize starch (24.4 *wt.*% amylose, 10 *wt.*% in total in solution) was achieved with 6.7 mol/mol water to [EMIM]Ac mixture (Zhang, Xie, Shamshina, Rogers, McNally, Halley et al., 2017). Maize

starch can be dissolved in this solvent within 1 h without apparently depolymerization. This provides a "green" way for the non-water sensitive processing of starch.

In addition to its use as solvents and catalysts for the chemical modification of starch, the applications of ILs as the plasticizer for the processing of starches have also been investigated. Sankri et al. verified the feasibility of plasticizing maize starch with [BMIM]Cl and a kind of electrically conductive thermoplastic starch (TPS) was obtained (Sankri et al., 2010). Compared with samples plasticized by glycerol, TPS modified by [BMIM]Cl showed a lower water uptake and higher elongation at break in its rubbery state. The results from a control experiment in their research showed that the structure of ILs and processing conditions probably play a significant role in the properties of the final product, but this still awaits deep studies. [BMIM]Cl was also used as a plasticizer for the processing of starch, zein and their blends with glycerol plasticized samples as control groups. According to the report by Leroy et al., [BMIM]Cl is a better plasticizer for maize starch than glycerol but has no obvious effects on the plasticization of zein (Leroy, Jacquet, Coativy, Reguerre, & Lourdin, 2012). However, in the blends of starch and zein, [BMIM]Cl was proved to be a good compatibilizer for the two components. This makes it possible for the production of biocomposites from raw natural polymers and has a potential application in food packaging and other areas. The performance of [EMIM]Ac as the plasticizer for the production of starch-based film was also studied in recent researches (Xie et al., 2014; Zhang et al., 2016). It's reported that compared with glycerol, [EMIM]Ac can disrupt the crystalline structure of starch more effectively and increase the mobility of amorphous region via replacing starch-starch interactions with stronger starch-[EMIM]Ac interactions. Consequently, the obtained IL plasticized TPS film displayed lower tensile strength and stiffness but higher flexibility. Better anti-aging and bio-stable performance were also noticed in the experiments when compared with films that use glycerol as the plasticizer. In another report, a transparent conductive TPS film was obtained by compression molding (8 MPa) of starch (24.4 % amylose) at 55 °C (or 65 °C) with [EMIM]Ac as plasticizer (Zhang, Xie, Shamshina, Rogers, McNally, Wang et al., 2017). The conductivity ($> 10^{-3}$ S/cm) of the film can be enhanced with a lower molding temperature (55 °C) and a higher relative humidity (RH, 75 %) during post-processing conditioning. This was related to the weak starch-[EMIM]Ac interaction at a lower temperature, and thus strong ion-pair dissociation. High RH, on the other hand, is preferable for the transference of ions in the film.

To be successfully applied to the production of biocompatible materials, there are still some problems to be overcome for ILs. For example, ILs are challenged in terms of "green" because of their poor performance in biodegradability, biocompatibility, and sustainability (Dai, van Spronsen, Witkamp, Verpoorte, & Choi, 2013). The relatively higher price of most ILs compared with that of conventional organic solvents also precludes their applications in most areas but high value-added products. In recent years, a new generation of environment-friendly solvents, consisting of hydrogen bond acceptor (HBA) and hydrogen bond donor(s) (HBD), was introduced as deep eutectic solvents (DES) (Smith, Abbott, & Ryder, 2014; Tavares, Rodríguez, & Macedo, 2013). Leroy et al. reported the plasticization of corn starch/zein blends with two choline chloride-based DES (choline chloride-urea (CC-U) and choline chloride-glycerol (CC-G)) (Leroy, Decaen et al., 2012). Their research showed that CC-U and CC-G can be used as an efficient functional plasticizer for TPS. Besides plasticization, these two DESs were also able to reduce the water sensitivity of TPS and act as a good compatibilizer for the blend of corn starch and zein. Very recently, the effect of DES (choline or betaine-based), IL ([EMIM] salts and $[NH_3CH_2CH_2OH][HCOO]$) and glycerol on the treatment of potato starch (16.5 *wt.*% water content) was compared (Zdanowicz, 2020). The results showed that urea-based DES (dissolving DES) and IL can dissolve potato starch while glycerol-based DES (non-dissolving DES) just gelatinized it. When used as plasticizer dissolving DES and IL resulted in TPS with a higher degree of amorphous than that of TPS from non-dissolving DES, thus lower tensile strength and much higher elongation at break as discussed previously on ILs. Like conventional ILs, this paper revealed that the composition of DES (the anion of choline salts and other components) also affect its performance on dissolving, plasticizing of starch as well as the mechanical properties of TPS. Another report, which studied 12 different DESs with choline chloride, betaine, malic acid, proline, lactic acid as HBA respectively, suggested that the composition of DESs affected the hydrogen-bonding formation between HBA anion and starch, consequently made great difference in their capacity to dissolve starch (Cao, Nian, Li, Wu, & Liu, 2019). All these results indicated that detailed systematic studies are needed for a thorough understanding of these influences on the DES application. Recently, several CC-based two-component DESs for starch dissolution and plasticization were summarized in one review (Zdanowicz, Wilpiszewska, & Spychaj, 2018). Not only CC-based DESs, imidazole-based two-component DESs were also prepared for starch dissolution and plasticization (Zdanowicz, Spychaj, & Maka, 2016). The performances of imidazole-choline chloride (IM-CC), imidazole-glycerol (IM-G), imidazole-citric acid (IM-CA) and imidazole-malic acid (IM-MA) on the dissolving and plasticizing of potato starch and high-amylose (> 68 %) starch were compared in this report. Unlike IM-CA and IM-MA, IM-CC and IM-G (ratio 7:3) turned out to be good plasticizers for both potato starch and high-amylose starch with 35 *wt.*%. DES in the mixture. The obtained transparent and elastic film exhibit an amorphous structure and no obvious retrogradation was observed after storage for one month. However, further evaluations like the degradation of starch in DES and mechanical tests on the obtained materials are still needed to verify the application potential of these DESs.

1.3. Supercritical CO_2

Supercritical fluids are defined as substances that are held at or above their critical point with a certain temperature and pressure, which makes the distinct interface between liquid and gas disappear. This kind of fluid possesses both the properties of gas and liquid-like low viscosity, high diffusion coefficient (Table 1) and good permeability and dissolving capacity. All the properties make the mass transfer process easier for chemical reaction or abstraction, which usually means a higher reaction rate or a faster abstraction than that in traditional solvents. Furthermore, there is a temperature and pressure zone near the critical point within which a slight change in temperature and (or) pressure will result in a significant change in density and many other properties, which enables the fluids to be tunable for different solutes. For all the reasons mentioned above, the applications of supercritical fluids have become a hot point for scientific research in recent decades. Among all the supercritical fluids that have been reported, water and supercritical CO_2 ($scCO_2$) are the most commonly used and commercially available fluids.

Compared with water (critical point: 647.14 K and 22.06 MPa), the supercritical conditions of CO_2 are relatively easy to achieve (304.12 K and 7.37 MPa) and the mild processing conditions, together with its chemical inertness makes $scCO_2$ an ideal solvent for many compounds that are easy to be damaged (Tommasi et al., 2017). Besides, the separation of $scCO_2$ by simply depressurization enables it to be more

Table 1
Typical values of physical properties of gases, supercritical fluids and liquids (Kemmere & Meyer, 2006).

Properties	Gas	Supercritical fluid	liquid
ρ (kg/m^3)	1	100 - 800	1000
η (Pa·s)	1×10^{-5}	1×10^{-5} - 1×10^{-4}	0.001– 0.1
D (m^2s^{-1})	1×10^{-5}	1×10^{-7}	1×10^{-9}

ρ, η and D stands for density, viscosity, and diffusivity respectively.

convenient and thus more economy than using other solvents. To the best of our knowledge, $scCO_2$ has been successfully used as a green solvent in many areas such as the extraction of caffeine from coffee beans and capsaicin from peppers, for dry cleaning and coating (de Aguiar et al., 2013; De Marco, Riemma, & Iannone, 2018; Liu, Zhang, Li, He, & Zhang, 2014; Ratcharak & Sane, 2014). In this part of the review, the application of $scCO_2$ as the solvent for polymer synthesis and processing was summarized with the hope that new ideas could be enlightened for the modification of starch.

1.3.1. Physical modification of starch with $scCO_2$

Normally, starches exist in nature in the form of granules with various diameters, depending on their botanical sources. Polarizing microscope observations and X-ray diffraction experiments have proved the existence of crystalline structures in starch granules. The crystalline zones have a significant influence on the processing of starches because they obstruct the accessibility of amorphous zones (Wang & Copeland, 2015). Thus, to get a deep knowledge of the structural change of starch macromolecules after modification, there have been many reports on the gelatinization of starches that is related to the disruption and breakdown of crystalline structures in granules (Ai & Jane, 2015; Carlstedt, Wojtasz, Fyhr, & Kocherbitov, 2015). Most of these experiments were carried out at various temperatures with water as medium and sometimes high pressure was applied. With a diffusivity that is two orders of magnitude larger than that of liquid solvents at relatively mild conditions as indicated previously, $scCO_2$ is believed to be a more effective solvent for the gelatinization of starches. To the best of our knowledge, Francisco and Sivik first reported the gelatinization of cassava, potato and wheat starch (72 % *wt./wt.* water content) with the assistance of CO_2 under different temperatures (50–70 °C) and pressures (up to 30 MPa) (Francisco & Sivik, 2002). An increase in the degree of gelatinization (DG) was found when the pressure was kept below 8 MPa, higher than which decreases in the DG were noticed. They concluded that the DG was positively related to the plasticizing effect of $scCO_2$, but negatively related to pressure. Muljana and Picchioni et al. also studied the effect of $scCO_2$ on the gelatinization of potato starch with various water content (16.2–40 % *wt./wt.*) (Muljana, Picchioni, Heeres, & Janssen, 2009). In their experiments, various temperatures (50–90 °C) and pressures (up to 25 MPa) were applied and a maximum DG of about 14 % (quantified by DSC) was observed at the pressure of 25 MPa and temperature of 90 °C. Contrary to the conclusion made by Francisco and Sivik with higher water content starch, the DG of lower water content starch was found to increase with increasing temperature and pressure. Except for these two papers, the influence of $scCO_2$ on the gelatinization temperature of different starch blends was also studied. In the research of Zaidul and Noda et al., different starches such as potato and cassava starch as well as their blends with wheat starch (70 % *wt./wt.* water content) at a series of ratios were gelatinized by $scCO_2$ treatment (20 MPa, 60 °C) (Zaidul, Noda, Sharif, Karim, & Smith, 2014). Decreases of 10–18 °C in the gelatinization temperature for all the samples were found via differential scanning calorimetry (DSC). They attributed this phenomenon to the pH changes caused by the contact of water with CO_2 and the plasticization of starch granules caused by $scCO_2$.

In addition to researches on $scCO_2$ induced gelatinization, many other studies on the application of $scCO_2$ in the processing of starches such as supercritical fluid extrusion (SCFX) and SCFX-based crosslinking have also been carried out. Chen and Rizvi et al. studied the relationships between the DG and rheology as well as the expansion properties of wheat starch-water mixtures under SCFX processing conditions (Chen & Rizvi, 2006). A reduction of 14 % in the apparent viscosity (measured between 100–200 s^{-1}) was found with the injection of 0.45 g $scCO_2$/100 g sample, regardless of the DG of mixtures. Their experiments also indicated a minimum DG of 80 % was required for the starch-water mixture to get a suitable gas-holding rheology for the production of extrudate with nonporous skin and desirable cellular morphology. In their later research, Rizvi and Ayoub's group reported the production of SCFX-based cross-linked starch microcellular foam (XL-SMCF) using wheat starch with epichlorohydrin (EPI) and sodium trimetaphosphate (STMP) as cross-linker respectively (Ayoub & Rizvi, 2008; Manoi & Rizvi, 2010). The results showed that using $scCO_2$ for the SCFX process could achieve good control over the expansion of extrudates as well as their microstructures via adjusting the injection rate of $scCO_2$. XL-SMCF from this experiment showed good water-resistance, which is favorable for its future application. Concerning the water-resistance property, a dual-modification of crosslinking and acetylation of corn starch was carried out in continuous $scCO_2$ extrusion and a more hydrophobic material was successfully achieved (Ayoub & Rizvi, 2011). A combination of SCFX and subsequent solvent exchange process was also studied in an attempt to get a deeper understanding of the influence of processing conditions on foam microstructure and macro-properties (Patel, Venditti, Pawlak, Ayoub, & Rizvi, 2009). The solvent exchange was proved, in this experiment, to be more important than other factors like crosslinking and the existence of $scCO_2$ for the formation of microcellular structures that have a great contribution to the brightness of material. Moreover, the brightness was also found to be linearly related to the density of the foams. In brief, starch foams produced by all these methods based on SCFX, with properties like low density, non-porous skin, and water resistance, have potential use as biodegradable materials.

Besides SCFX, the application of $scCO_2$ for tissue engineering, pharmaceutical processing and the production of antimicrobial materials have been explored in recent years. For instance, a supercritical immersion precipitation technique was used by Duarte et al. to evaluate the feasibility of using chloroform or dichloromethane as solvent and $scCO_2$ as a non-solvent for the preparation starch-polylactic acid scaffold for tissue engineering (Duarte, Mano, & Reis, 2009). A matrix with high porosity and interconnected microstructure was obtained by supercritical assisted phase-inversion (10–20 MPa, 35–55 °C, 45 min). Both pressure and blend composition were proved to play important roles in controlling the morphology of the scaffold. Pure starch aerogel was also prepared to obtain low-cost biodegradable material for applications in pharmaceuticals (Ubeyitogullari & Ciftci, 2016). Wheat starch (10 *wt.*%) was first gelatinized in water and solvent-exchange with ethanol followed which was removed subsequently by $scCO_2$ (10 MPa, 40 °C). The aerogel obtained at a low CO_2 flow rate (0.5 L/min) has a maximum surface area of 59.7 m^2/g. The reason is that low CO_2 flow can prevent the "growing" of the ethanol drop in the matrix. A similar procedure was also used in another report for the preparation of starch aerogel thermal superinsulation material (Druel, Bardl, Vorwerg, & Budtova, 2017). The obtained results suggest that starch (8 *wt.*%) with higher amylose content produced aerogel with lower density and higher specific surface area (254 m^2/g). A possible explanation is amylose can form stronger networks during retrogradation, thus resist shrinkage during subsequent solvent-exchange. It should be noted that pure amylose, however, did not work due to the heterogeneous structure (resulted from the fast retrogradation progress) that cannot stand the pressure during drying (8 MPa, 37 °C). In addition to the production of the scaffold and aerogel, starch can also be used for the delivery of bioactive material. For example, Varona et al. impregnated lavandin oil into n-octenyl succinate modified waxy maize starch and the influences of different operational conditions like lavandin oil to starch mass ratio, pressure as well as temperature were analyzed (Varona, Rodríguez-Rojo, Martín, Cocero, & Duarte, 2011). Higher impregnation loads were observed at a relatively low concentration of $scCO_2$ fluids (low pressure, e.g., 10 MPa for 2 h) and a high depressurization rate (e.g., within 1 min). It is believed that low pressure could weaken the interactions between $scCO_2$ and solutes in it, which is favorable to strengthen the interactions between solutes and starch. High depressurization rate, on the other hand, could facilitate the condensation of lavandin oil. The droplets formed in this process deposited in starch particles and thus increased the impregnation load. Another important factor that

influences the efficiency of impregnation is solubility and diffusion of solutes in $scCO_2$. For example, Comin et al. found that simple lipids like oleic acid had a higher load (optimum: 15 MPa, 40 °C for 8 h) on pregelatinized corn starch than flax oil (optimum: 30 MPa, 80 °C for 8 h) which is a more complex lipid mixture (Comin, Temelli, & Saldaña, 2012). They attributed this to oleic acid's higher solubility and diffusion coefficient in $scCO_2$ than that of flax oil. In the research carried out by Souza et al., a kind of antimicrobial film was successfully developed by impregnating cinnamaldehyde into cassava starch-based film (de Souza, Dias, Sousa, & Tadini, 2014). The highest impregnation load was achieved at a higher pressure (25 MPa, 35 °C for 15 h) which is opposite to that mentioned by Varona et al. A conclusion was drawn that the solubility of cinnamaldehyde in $scCO_2$ played a vital role in the impregnation process. No impregnation products from the above-mentioned researches showed a porous structure. In one recent report, potato starch aerogel (185 m^2/g) impregnated with green coffee oil was prepared via a one-pot process (Villegas, Oliveira, Bazito, & Vidinha, 2019). This procedure integrated gelatinization, retrogradation and drying (20 MPa, 40 °C, 2 ml/min CO_2) with impregnation process. Moreover, no solvent-exchange process was needed to fabricate the aerogel, which is different from aforementioned reports. However, like conventional solvent-exchange procedure, the long retrogradation period (at least 24 h) for the buildup of internal structure to prevent shrinkage is still the efficiency barrier for the preparation of starch aerogel.

1.3.2. Chemical modification of starch in $scCO_2$

Although there are many advantages to use $scCO_2$ as the solvent for chemical reaction and many reports on this kind of application have been published, papers on the chemical modification of starches in $scCO_2$ are still very few (Table 2).

Muljana et al. reported the synthesis of fatty acid-starch esters in $scCO_2$ with different vinyl, methyl esters as esterification reagents (Muljana et al., 2010). The highest degree of substitution (DS = 0.31, 150 °C and 8 MPa for 18 h) was obtained with the combination of vinyl laurate and K_2CO_3. In their later work, the acetylation of potato starch with acetic anhydride (Ac_2O) was studied in sub- and supercritical CO_2 medium (Muljana, Picchioni, Knez, Heeres, & Janssen, 2011). The DS was evaluated within a broad range of pressure (8–25 MPa) at 90 °C and the highest DS of 0.29 and 0.62 (corresponding to 1 h and 24 h reaction time respectively) were obtained near the critical point of the mixture (15 MPa). Besides, the DS was found to relate with the size of starch granules, which means the mass transfer inside the granule plays a more important role than intrinsic reaction kinetics in controlling the overall conversion rates. Apart from the esterification and acetylation, the grafting of starch was also studied with $scCO_2$ as the solvent. Salimi et al. reported that up to 52 % poly(*L*-lactic acid) was successfully grafted onto pregelatinized corn starch by controlled polymerization with stannous 2-ethyl hexanoate ($Sn(Oct)_2$) as a catalyst in $scCO_2$ (20 MPa, 100 °C for 6 h with starch/lactic acid ratio = 1:3) (Salimi, Yilmaz, Rzayev, & Piskin, 2014). High pressure, temperature and flow rate of $scCO_2$ were observed unfavorable to the chain growth. However, a relatively higher temperature was proved acceptable for chain growth when the flow rate of $scCO_2$ was maintained at a relatively lower value.

2. Controlled modification of starch

Chemical modification, which could expand the application of starch to areas beyond imagination (e.g., medical plasma expander and drug carrier, drilling fluid in oilfield, film, and foam in packaging), has been under investigation for a long time. As is known, the application fields of materials are determined by their intrinsic properties that are closely related to their microstructures. In the case of polymers, their microstructures are influenced by the composition and structure of both backbones and side chains or groups. According to this principle, varieties of starch derivatives with different properties can be got by:

- substituting hydroxyl groups with other functional groups;
- grafting side chains with different composition, length, and structure;
- varying the distribution of groups or chains along the backbone.

Lots of work has been carried out following the three mentioned guidelines. Compared with traditional chemical methods, from our point of view, the controlled modification of starch is of great interest as it could provide us with functional products that have tailor-made properties for specific applications. Another advantage of controlled modification is, as will be illustrated in the following part, that some properties can even be achieved or enhanced just by the switching of reaction sites. For this reason, much research has been done on the controlled modification of starches during the last decades. In this part of the review, attention was paid to the progress on the controlled modification of starches with the hope that more efficient work could be done in the future.

2.1. Regioselective functionalization of OH-groups

For polysaccharides like starch, the existence of three hydroxyl groups with different chemical environments in the AGU provides us the possibilities to achieve derivatives that have the same side groups/chains but different properties. For example, after preserved at room temperature for a hundred days a significant degradation can be observed in the starch acetate prepared according to the conventional procedure (acetylation of starch in an aqueous medium with acetic anhydride as the reagent). On the contrary, regioselective synthesized 2-*O*-acetyl starch can be stored in sterilized distilled water for over 200 days without significant change in viscosity and only a slight decrease in the DS was observed (Liebert, Kulicke, & Heinze, 2008). Significant increases in the viscosity (400 % higher), glass transition temperature and degradation temperature (34 °C and 36 °C higher respectively) were also observed in the 2-*O*-acetyl starch when compared with conventional acetylated starch that has the same DS (Dicke, 2004). A possible explanation for this is the more uniform structure resulted from regioselective derivatization enhances intra- and intermolecular interactions (hydrogen bonds or hydrophobic interactions) and thus improves the macro-properties of the products. Besides, 2-*O*-acetyl starch only swells in water while conventional starch acetate was soluble with similar DS. Another interesting report was that 2-*O*/3-*O*- acetyl starch had a higher biodegradation rate than 6-*O*- acetyl starch when exposed to α-amylase (Roesser, McCarthy, Gross, & Kaplan, 1996). Clearly, the regioselective functionalization could endow starch derivatives with novel properties with currently available reagents thus expand the application fields of starches, especially in areas like biomaterials.

As far as we know, the regioselective functionalization of polysaccharide has been studied for over 50 years. Generally, there are three approaches available now for the effective regioselective functionalization of polysaccharides (see below):

- protection and deprotection approach in which bulky protecting groups such as silyl and trityl groups are employed for the preparation of 6-*O* or 2,6-*O* protected intermediates (Petzold, Koschella, Klemm, & Heublein, 2003; Wang, Yang et al., 2015);
- catalyzed selective functionalization of OH groups without using protecting groups (enzymes, inorganic salts, etc.) (Chakraborty, Sahoo, Teraoka, Miller, & Gross, 2005; Wang, Qu, Wu, Men, & Liu, 2017);
- regioselective replacement of OH groups with other functional groups through reactions controlled by a stereochemical mechanism (S_N2 reaction etc.) (Gao, Liu, & Edgar, 2018; Tan, Li, Gao et al., 2017).

2.1.1. Protection and deprotection approach

Two different regioselective approaches, in which toluenesulfonyl

Table 2
The application of $scCO_2$ in the modification of starches and corresponding general processing conditions.

Method	Application	Pressure/MPa	CO_2 ratio g/100 g sample	Temperature/ ˚C	Solvent	Water content/*wt.*%	Time/h	Starch source	DG/%	Reference
Physical	Gelatinization	8 - 30	*N.A.*	50 - 70	*N.A.*	72	0.33	Cassava, potato and wheat	*N.A.*	(Francisco & Sivik, 2002)
		0.1 - 25		50 - 90		16.2 - 40	1	Potato		(Muljana et al., 2009)
		20		60		70	1	Cassava, potato and sweet potato		(Zaidul et al., 2014)
	SCFX	~10	0.45	~50	*N.A.*	42	*N.A.*	Wheat starch	80	(Chen & Rizvi, 2006)
		~10	0.5 - 1	~70		45		Wheat starch	*N.A.*	(Manoi & Rizvi, 2010)
		~10	1	~70		45		Corn starch		(Ayoub & Rizvi, 2011)
		~10	1	~70	Ethanol	35		Corn starch		(Patel et al., 2009)
	Phase-inversion	10 - 20	*N.A.*	35 - 55	Chloroform, Dichloromethane	*N.A.*	0.75	*N.A.*	*N.A.*	(Duarte et al., 2009)
	Aerogel	10 - 15	0.5 – 1 L/min ***a***	40 - 50	Ethanol	85 - 95	4	Wheat	*N.A.*	(Ubeyitogullari & Ciftci, 2016)
		8	0.4 MPa/h ***a***	37	Ethanol, Acetone	89 - 95	6 – 8	Waxy/regular potato, pea, high amylose corn		(Druel et al., 2017)
		10 - 20	0.12 L/min ***a***	40 - 120	Ethanol	85 - 95	~ 50	Potato		(Villegas et al., 2019)
	Impregnation	10 - 12	0.07 – 12 MPa/min ***a***	40 - 50	*N.A.*	*N.A.*	2	n-octenyl succinate (OSA) modified waxy maize starch	*N.A.*	(Varona et al., 2011)
		15 - 30	1 L/min ***a***	40 - 60			6	Pregelatinized corn starch		(Comin et al., 2012)
		15 - 25	0.1 – 1 MPa/min ***a***	35			3 - 15	Cassava		(de Souza et al., 2014)

Method	Application	Pressure/MPa	scCO2 Flow rate g/min	Temperature/ ˚C	Solvent	Water content/*wt.*%	Time/h	Starch source	Catalyst	Reference
Chemical	Esterification	6 - 25	*N.A.*	120 - 150	*N.A.*	16.2	6 - 18	Potato	K_2CO_3, TEA, NaOAc, Na_2HPO4	(Muljana et al., 2010)
	Acetylation	8 - 25		90		16.2	1 - 24	Potato	NaOAc	(Muljana et al., 2011)
	Grafting	7 - 30	1 - 15	70 - 110	Water	*N.A.*	1.5 - 9	Corn	Stannous 2-ethyl hexanoate	(Salimi et al., 2014)

a: Depressurization rate was used instead of CO_2 ratio.

(tosyl) and triphenylmethyl (trityl) groups were employed as leaving/protecting groups for the introduction of 3,6-anhydro rings into amylose, were reported by Whistler et al. (Whistler & Hirase, 1961). Results showed that the trityl group had better regioselectivity on the derivatization of primary hydroxyl groups than the tosyl group. However, it should be noticed that the detritylation process carried out in the acid medium may cause the breakdown of polysaccharide chains. Besides the groups mentioned above, the silyl group has also been used for the regioselective functionalization of starches. For instance, a highly regioselective approach that using thexyldimethylchlorosilane (TDSCl) as protecting reagent was developed by Petzold et al. for the protection of primary hydroxyl groups in potato starch (Petzold, Einfeldt, Günther, Stein, & Klemm, 2001). The silylation of potato starch was carried out in the mixture of *N*-methylpyrrolidone (NMP) and ammonium at -20 °C. Different from their another research in which the silylation was carried out in the mixture of DMSO and pyridine (Einfeldt et al., 2001), 6-*O*-TDS starch ether could be obtained exclusively by this approach with a DS up to 1 even when the TDSCl was excessive. The introduced protecting group can be easily removed by the treatment with tetrabutylammonium fluoride (TBAF) solution in THF (R.T. to 50 °C, 14–24 h) (Petzold, Klemm, Stein, & Günther, 2002). Besides the TDS group, TBAF or tetrabutylammonium hydroxide (TBAOH) can also be used for the efficient deacylation of potato amylose tripropionate (R.T. to 50 °C, 1–24 h) to obtain highly regioselective amylose-6-*O*-ester (Zhang, Zheng, Kuang, & Edgar, 2014). Nevertheless, the protection-deportation approach is time-consuming and especially not atom economy for large-scale applications.

According to the aforementioned researches, not only the structure of the protecting reagent affects the selective protection of hydroxyl groups, but the reaction medium also has a significant influence on the regioselectivity. One example is the tosylation of starch. In the researches carried out by Whistler et al. and Clode et al., pyridine was used as the reaction medium for the tosylation of amylose and results shown that this process mainly occurred at the C-6 position (Clode & Horton, 1971; Whistler & Hirase, 1961). However, after switching the reaction medium to the mixture of DMAc and LiCl the tosylation at the C-2 position was found more preferable than that occurred at C-6 and C-3 position (Dicke, Rahn, Haack, & Heinze, 2001). The influence of solvent on the regioselectivity of protecting groups was related to the supramolecular structure of the polymer formed in specific conditions, but no evidence is available now and further studies are needed to support this hypothesis.

2.1.2. Catalyzed regioselective functionalization

Besides the utilization of protecting groups, regioselective derivatization of polysaccharides can also be achieved directly by using enzymes, catalytic active salts and heterocyclic compounds such as pyridine to promote the reaction. As for the enzyme-catalyzed site-selective functionalization, one problem faced is that the use of polar aprotic solvents, which are used to dissolve polysaccharides, may decrease the activity of enzymes (Klibanov, 1997). To overcome this problem, an approach developed by Paradkar and Dordick was employed by Bruno et al. to incorporate *Subtilisin Carlsberg* into surfactant micelles for the regioselective acylation of amylose film (Bruno et al., 1995; Paradkar & Dordick, 1994). Although this research was carried out successfully, only the surface of the amylose film was accessible for the enzyme and thus the efficiency of functionalization was not satisfactory. In the research carried out by Chakraborty et al., a new approach was proposed to solve this problem (Chakraborty et al., 2005). Starch nanoparticles were incorporated into Aerosol-OT (AOT, bis(2-ethylhexyl)sodium sulfosuccinate) micelles to improve its accessibility to immobilized *Candida antartica Lipase B* (*CAL-B*). As a comparison, free *CAL-B* was also incorporated into AOT micelles together with starch nanoparticles in the control experiments. The esterification of AOT-coated starch nanoparticles was carried out with toluene as solvent in which vinyl stearate, ε-caprolactone, and maleic anhydride were dissolved respectively as esterification reagent (mole ratio of reagent: AGU = 3:1). Starch-6-*O*-esters were obtained with DS ranging from 0.8 to 0.4 after reaction at 48 °C for two days. Results showed that the catalyzed esterification process, whether the *CAL-B* was immobilized or not, was regioselective for the primary hydroxyl groups in the AGU. However, considering the post-purification, immobilized *CAL-B* is preferable for this approach. An alternative to the aforementioned approach was reported by Klohr et al., by whom protease was employed to achieve the regioselective functionalization of C-2 position (Klohr, Koch, Klemm, & Dicke, 2005). In their reported approach, protease was first activated in phosphate buffer solution (pH = 7.8, c = 0.15 M) and then lyophilized before added to the starch/DMSO solution. Various esterification reagents, such as vinyl acetate, acetic anhydride or propiolactone can be used for the regioselective substitution of starch in this approach and DS up to 1 can be reached. One thing should be noted is that chemical esterification may occur besides the enzyme-catalyzed reaction when this reaction is carried out at 40 °C. To substantially suppress the chemical reaction, the esterification procedure can be carried out at a lower temperature (20–25 °C) or conducted in an almost anhydrous system (water content < 0.01 %).

In addition to the enzyme, several salts and heterocyclic compounds can also catalyze the regioselective functionalization of starches. The differences are that the latter one can modify starch homogenously and the regioselective site usually is C-2 instead of C-6 from that of the enzyme. For instance, nine different salts (Table 3) were tested by Dicke for the catalyzed regioselective acetylation of starches in DMSO and their performances in regioselectivity were compared with that of DMAP/pyridine (Dicke, 2004). These salts, according to their site-selectivity and the pH values of their aqueous solutions, were divided into three types. High regioselectivity at the C-2 position was shown when using neutral, weak acid or alkaline salts as catalysts, while further acetylation would occur to some extent at C-6 and C-3 position when alkaline salts were employed. No catalytic activity was found when acid salt was employed as a catalyst. The regioselectivity in DMSO was related to the formation of intramolecular hydrogen bonds between the C-2 hydroxyl groups and that in the C-3 position of the neighboring AGU (Fig. 3). The formation of these hydrogen bonds, together with other factors such as solvent and ring oxygen, was believed to make the protons of C-2 hydroxyl groups have a stronger acidic character than the other two protons. However, it should be kept in mind that there is still no evidence to prove this hypothesis. In a more recent paper, the regioselective preparation of starch-based macroinitiator for ATRP in DMSO and imidazolium-based ILs ([AMIM]Cl, [EMIM]Ac, [EMIM]DMP and [EMIM][(MeO)HPO_2]) was also compared (Wang et al., 2017). According to this report, the acylation of starch with vinyl chloroacetate in DMSO with sodium carbonate as catalyst mainly occurs at

Table 3
The influence of catalysts, catalyst concentration, and acetylation agents on total and partial DS of starch acetate (Dicke, 2004).

Reaction conditions			Starch acetate			
Catalyst	c(cat)/*wt.*%	Acetylation reagent	DS_{total}	DS_{C2}	DS_{C6}	DS_{C3}
DMAP/pyridine	2	Acetic anhydride	1.00	0.37	0.50	0.13
Na_2HPO_4	2	Acetic anhydride	1.00	0.69	0.20	0.11
Na_2HPO_4	2	Vinyl acetate	1.00	1.00	0	0
NH_4Cl	2	Vinyl acetate	0.95	0.95	0	0
NaCl	2	Vinyl acetate	1.00	1.00	0	0
Na-citrate	2	Vinyl acetate	0.80	0.80	0	0
Na_2CO_3	2	Vinyl acetate	1.00	1.00	0	0
Na_2CO_3	5	Vinyl acetate	1.82	1.00	0.55	0.27
K_2CO_3	2	Vinyl acetate	2.18	1.00	0.72	0.46
K_3PO_4	2	Vinyl acetate	1.03	1.00	–	0.03
Mg-acetate	2	Vinyl acetate	1.15	1.00	0.05	0.10
Na-acetate	2	Vinyl acetate	1.82	0.91	0.37	0.54

*Reaction conditions: 40 °C, 70 h, 2.3 mol acetylation agent/mol AGU.

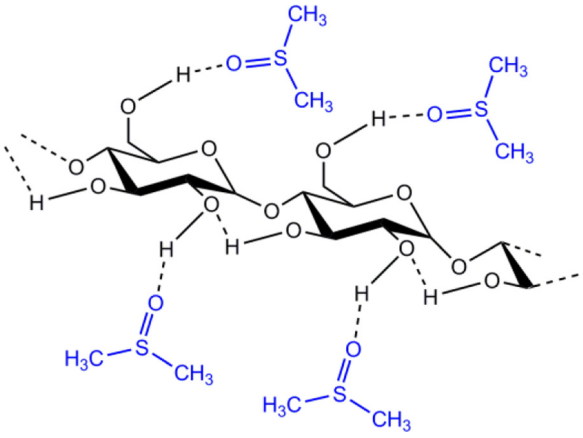


Fig. 3. Solution state of starch (amylose) in DMSO (Dicke, 2004).

the C-2 position (DS up to 0.15, 40 °C, 192 h) which is in line with the results from Dicke et al., while reactions in ILs shows no regioselectivity. Besides the type of salt, regioselectivity was also influenced by the amount of salts used as well as the type of acetylation reagent (Table 4). The latter factor was attributed to their differences in reactivity. The regioselective substitution of C-2 hydroxyl groups was also achieved by Liebert et al., in the study of whose starches were acetylated homogeneously by acetic acid/*N,N'*-carbonyldiimidazole (CDI) and acetic anhydride/imidazole respectively with DMSO as solvent (mole ratio of esterification reagent: base (imidazole): AGU = 1.3:1.3 ~ 3:1) (Liebert et al., 2008). Starch acetates with DS ranging from 0.4 to 1.23 can be obtained after a reaction at 60 °C for two hours and then kept at room temperature for another 16 h. In both cases, high regioselectivity at the C-2 position can be detected and was contributed to the formation of reactive intermediate (acetic acid imidazolide) and the possible solution state of starch in DMSO.

The same approach was also employed by Hampe et al. to study the influences of solvent and many other factors (such as molecular weight and the concentration of starch) on the substitution patterns of starch acetate (Hampe & Heinze, 2014). Another approach used in their experiment was acetylating different starches by acetic anhydride with molten imidazole as the solvent and the reaction was kept at 100 °C for one hour. When using DMSO as the solvent, potato starch was acetylated predominately at the C-2 position and the DS increased (up to 0.71) with a higher molar ratio of acetic anhydride to AGU (reagent/AGU ratio up to 1.0). However, an even higher reagent/AGU ratio, which could result in additional acetylation of the C-6 hydroxyl groups, was needed to get similar DS at the C-2 position for degraded potato and tapioca starches. One possible explanation proposed for this was that degradation, as well as the branching points, reduced the amount of 2,3-hydrogen bonds between adjacent AGUs thus the 2-*O* proton had less activity for acetylation. Another interesting found was that, besides the reagent/AGU ratio, increasing the concentration of degraded starches in DMSO could also promote the acetylation of primary hydroxyl groups. When molten imidazole was used as the solvent, in contrast to that occurred in DMSO, regioselective acetylation at the C-6 position was found at a low reagent/AGU ratio (≤ 0.5 and 0.3 for potato and degraded potato starch respectively). At higher reagent/AGU ratio, hydroxyl groups at C-2/C-3 positions could also be acetylated and resulted in a random distribution of acetyl moieties.

2.1.3. Regioselective replacement of OH groups

Besides regioselective esterification, etherification and so on, the hydroxyl groups could also be selectively replaced by various nucleophiles (such as oxygen, nitrogen and sulfur nucleophiles) through S_N2 reaction (as seen in Fig. 4) (Cumpstey, 2013). To achieve this purpose, a good leaving group is needed to make the target carbon atom more susceptible to the attack of nucleophiles. Commonly used leaving groups are sulfonates ($RS(O)_2O$-) and halides.

In the research carried out by Whistler et al., the tosylate group was employed for the introduction of 3,6-anhydro rings into amylose (Whistler & Hirase, 1961). According to the reported procedure, amylose was first tosylated at the C-6 position (35–60 °C) and then the introduction of 3,6-anhydro rings was realized through the substitution of

Table 4
Summary of the regioselectivity of different methods for the modification of starch.

Method	Solvent	Protecting group/ Catalyst	Regioselectivity [a]	DS [b]	Reference
Protection-deprotection	NMP/ammonia	Silyl group	6-*O*	1	(Petzold et al., 2001)
	DMSO/pyridine	Silyl group	6-*O*	1	(Einfeldt et al., 2001)
	Pyridine	Trityl	6-*O*	1	(Wolfrom & Wang, 1970)
	DMAc/LiCl	Propionyl group	6-*O*	1	(Zhang et al., 2014)
	Pyridine	Trityl	6-*O*	1	(Whistler & Hirase, 1961)
	Pyridine	Tosyl	6-*O*	0.76	
	DMAc/LiCl	Tosyl	2-*O*	~ 0.73	(Dicke et al., 2001)
Catalyzed derivatization	Toluene	*CAL-B*	6-*O*	0.8 - 0.4	(Chakraborty et al., 2005)
	DMSO	Protease	2-*O*	1	(Klohr et al., 2005)
	DMSO	Mainly sodium salts	2-*O*	0.7 - 1	(Dicke, 2004; Wang et al., 2017)
	DMSO	CDI (Imidazole)	2-*O*	0.4 - 1	(Liebert et al., 2008)
	Molten imidazole	Imidazole	6-*O*	0.3 - 0.5	(Hampe & Heinze, 2014)

Method	Solvent	Leaving group/ Catalyst	Regioselectivity [a]	DS [b]	Reference
Regioselective replacement	Pyridine	Tosylate	C-6	0.76	(Whistler & Hirase, 1961)
	Pyridine	Tosylate	C-6	~ 0.62	(Clode & Horton, 1971)
	DMAc/LiBr (LiCl)	Br (Cl)	C-6	~ 1	(Cimecioglu et al., 1994; Tan, Li, Dong et al., 2017)
	DMF/LiN_3	Br	C-6	~ 1	(Cimecioglu et al., 1997)
	DMF/NaN_3 ($DMAc/ NaN_3$)	Br	C-6	~ 1	(Barsi et al., 2017; Shey et al., 2006)
	Water	TEMPO/NaBr/ NaClO	C-6	0.95	(Chang & Robyt, 1996)
	Water	TEMPO/NaClO	C-6	0.68	(Bragd et al., 2000)

[a] The most preferable reaction site.
[b] The largest partial degree of substitution could be got before other secondary hydroxyl groups are substituted.

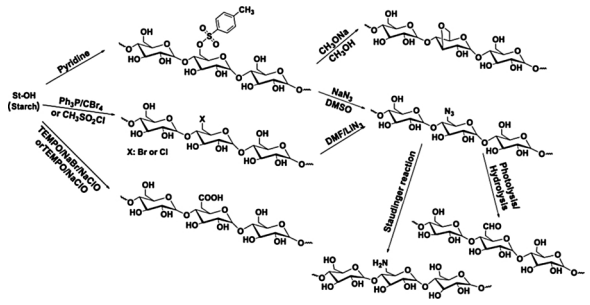


Fig. 4. Reaction scheme for the regioselective replacement of starch.

C-6 tosylate group by the oxygen at the C-3 position under alkaline conditions. Another example for the application of the tosylate group was reported by Clode and Horton, in whose research both potato amylose and whole starch were tosylated in pyridine (35–60 °C, 0.5–2 h) and then converted to corresponding 6-azido-6-deoxy derivatives (7 h, 80 °C, DS 0.62 and 0.92 respectively) with DMSO as solvent (Clode & Horton, 1971). 6-aldehydo-amylose (DS 0.48) and 6-aldehydo-starch (DS 0.57) can be achieved through the photolysis and successive mild hydrolysis of corresponding 6-azido-6-deoxy derivatives.

In addition to tosylate groups, halides were also proved good leaving groups for the regioselective derivatization of starches. In one research carried out by Cimecioglu et al., 6-halogen-6-deoxyamylose with DS up to 1 was synthesized by the reaction of amylose with Ph_3P/*N*-bromosuccinimide (NBS) and methanesulfonyl chloride respectively with DMF/LiBr (LiCl) as solvent (70 °C, 2 h) (A. Cimecioglu, Ball, Kaplan, & Huang, 1994). The halides were replaced by azide (70 °C, 48 h) and then Staudinger reaction was employed to reduce azide to amine. 6-amino-6-deoxyamylose with DS up to 1 can be achieved according to this approach. A similar method was also employed in some recent researches for the preparation of 1,2,3-triazolium-functionalized starch with antifungal properties (80 °C, 3 h for bromination, 80 °C, 24 h for azidation) (Tan, Li, Dong et al., 2017; Tan, Li, Gao et al., 2017; Tan et al., 2016). Although the halogenation procedure was proved to be high regioselective, degradation was reported when a similar approach was employed for the chlorination of chitin with excess *N*-chlorosuccinimide at a relatively higher temperature (Sakamoto, Tseng, & Furuhata, 1994). Besides, the described procedure for the preparation of 6-azido-6-deoxyamylose was also time-consuming and not economical. To overcome these problems, a more direct and mild approach was introduced by Cimecioglu et al. for the azidation of amylose (Cimecioglu, Ball, Huang, & Kaplan, 1997). Amylose was dissolved in the mixture of DMF/LiN_3 and then Ph_3P, as well as the freshly prepared CBr_4/DMF solution, were added successively. This homogeneous reaction system was kept at room temperature for about 18 h with the protection of nitrogen. According to this approach, 6-azido-6-deoxyamylose can be achieved with nearly all the primary hydroxyl groups substituted. Given the high price of amylose, this one-pot approach has been extended to the azidation of different starches in recent years. For example, in one recent research potato amylose and maize amylopectin were functionalized with photochromic spiropyran via the combination of this method and Cu(I)-catalyzed azide-alkyne cycloaddition (CuAAC) (Barsi et al., 2017). This modified starch could be a promising photochromic coating for substrates like paper and leather. Lithium azide, because of its high hygroscopicity and the resulting adverse effect on azidation, was replaced with sodium azide by Shey et al. (Shey et al., 2006). Not only DMF, but DMAc was also used as the solvent in their experiments. In both cases, pregelatinized starches can be derivatized with high regioselectivity at the C-6 position while no desirable result could get from those untreated starches. This was attributed to the low solubility of untreated starch granules.

Besides S_N2 substitution, another reported stereochemically controlled reaction is 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO)-mediated oxidation of starch. One example is the successful oxidization of various polysaccharides (starch included) reported by Chang et al. (Chang & Robyt, 1996). Results showed that polysaccharides, whether water-soluble or not, could be oxidized with high regioselectivity at the C-6 position by using TEMPO with sodium bromide/sodium hypochlorite as co-catalyst (DS = 0.95, pH = 10.8, 0 °C, 0.75–1.8 h). The high regioselectivity of this reaction was related to the steric hindrance caused by the bulky TEMPO ion as well as the conformation of AGU. Despite the high selectivity, the practical application of this technique was hindered by the use of bromide which is considered to be hazardous to both environment and production equipment. To overcome this problem, a bromide-free approach in which TEMPO ion can be directly generated by hypochlorite was reported by Bragd et al. (Bragd, Besemer, & van Bekkum, 2000). According to this approach, high regioselectivity can be achieved with a significant suppression on the degradation of molecular chains when the reaction was carried out under suitable conditions (temperature ≤ 20 °C and pH < 9). Considering the comparable reaction rate (DS = 0.68, 20 °C, pH = 8.5, 0.75–2 h) to that of bromide co-catalyzed reaction (DS = 0.7, pH = 8.5, 2 °C, 2–5 h), this approach should be a good alternative for the conversion of primary alcohol groups into aldehyde and carboxyl groups.

For clarity, the reported methods for regioselective modification of starch are summarized in Table 4. As suggested in the table, while most of the protection-deprotection and region-replacement methods aim at the C-6 position, catalyzed derivatization mainly generates C-2 modified starch. So far as we know, there is still no report on the C-3 selective derivatization available. The applications of green solvents like ILs are either failed (salt-catalyzed method) or not reported yet.

2.2. Controlled grafting of starch

Compared with starches modified through the substitution of hydroxyl groups with small molecules, such as hydroxyethyl starch and cationic starches, brushed starches have some unique properties which can expand the application of starch-based materials as high value-added products. For example, amphiphilic branched starches have been synthesized as potential drug carriers with the property of self-assemble (Li et al., 2015; Wu et al., 2016; Yang et al., 2014). Besides, many other grafted-starches have also been reported for various applications such as biodegradable polymers, absorbents, and enhanced oil recovery (EOR) (Dragan, Apopei Loghin, & Cocarta, 2014; Najafi Moghaddam, Fareghi, Entezami, & Ghaffari Mehr, 2013; Song, Zhang, Ma, Wang, & Yang, 2007). As it is known, there are many other factors besides the botanical sources of starches have a significant influence on the properties of final branched products. For instance, the intrinsic properties of branch chains, as well as their grafting density and length, are directly related to the rheological and mechanical properties of modified starches. To achieve a successful application of these materials, it is of great importance to have a deep knowledge of the relationship between macroscopic properties and microstructures. Thanks to the development of techniques in controlled/living polymerization, many new approaches have been adopted for the synthesis and analysis of branched starches in recent years. In the following part of this review, the progress and open questions in the controlled modification of starch with techniques like metal-catalyzed living radical polymerization (mainly atom transfer radical polymerization (ATRP) and Cu°-mediated living radical polymerization (Cu°-mediated LRP)), reversible addition-fragmentation chain transfer (RAFT), nitroxide-mediated polymerization (NMP), “click” and chemoenzymatic methods are summarized.

2.2.1. Metal-catalyzed living radical polymerization

Techniques used for metal-catalyzed living radical polymerization can be categorized into two main groups, which are known as ATRP and Cu°-mediated LRP (or single-electron transfer living radical polymerization (SET-LRP)), according to the differences in the reaction

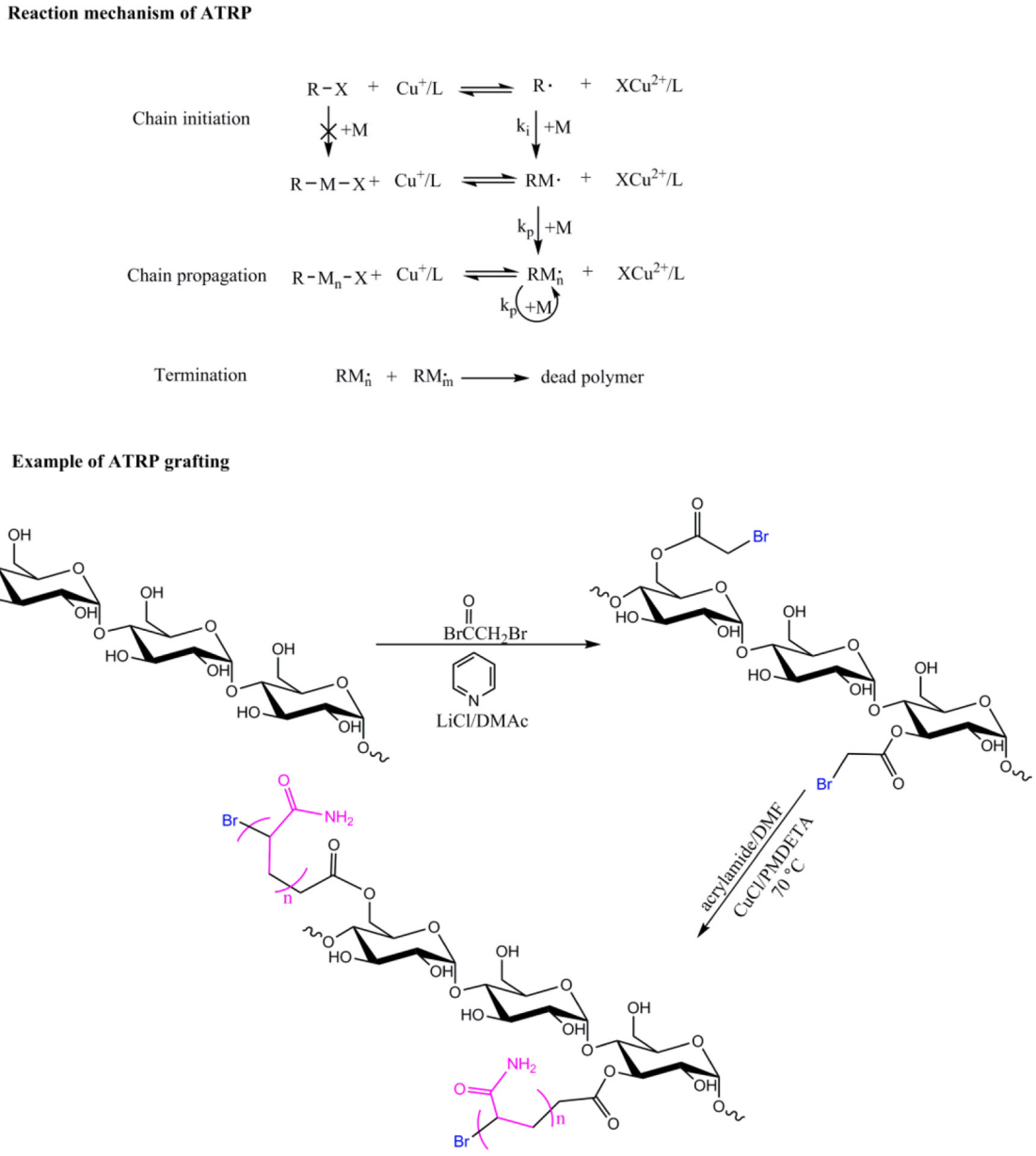


Fig. 5. The reaction mechanism for ATRP and an example of its application in starch modification.

mechanism. Metal-catalyzed living radical polymerization is one of the most widely used controlled polymerization techniques for the preparation of polymers with defined architectures, through which desirable properties as predesigned can be achieved conveniently. Many works have been done on this subject since Wang et al. reported the first paper in 1995 and the progress of this technique has been kindly reviewed (Anastasaki et al., 2016; Boyer et al., 2016; Ding, Jiang, Zhang, Cheng, & Zhu, 2015; He, Jiang, Zhang, Cheng, & Zhu, 2013; Matyjaszewski, 2012; Wang & Matyjaszewski, 1995). According to literature, most of the reported controlled grafting of starches were accomplished by ATRP (see example in Fig. 5).

Surface-initiated atom transfer radical polymerization (SI-ATRP) was first employed by Liu et al. for the grafting of potato starch granules with the hope that grafted starches could be used for the production of biodegradable plastics (Liu & Su, 2005). Bromoacetyl bromide was immobilized onto the surface of starch granules in the first step then poly(n-butyl acrylate) was grafted from the surface of the macroinitiator with CuBr/1,10-phenanthroline as the catalyst in toluene. A 9.9 % of monomer conversion was achieved after polymerization for 5 h. Similar method was also used by Moghaddam et al. in the modification of starch surfaces with polystyrene (PS) and polyacrylamide (PAM) to develop biodegradable thermoplastic copolymers (Najafi Moghaddam et al., 2013). In another research reported by their group, both free radical polymerization and ATRP were used for the synthesis of starch-g-polyacrylamide and starch-g-polyhydroxyethylacrylate and the performance of copolymers in controlled release of cephalexin antibiotic were compared (Avval, Moghaddam, & Fareghi, 2013). Results showed that it would take a longer time for copolymers obtained from the ATRP method to release all the loaded drugs. It was attributed to the more orderly chain length and larger graft densities (2.51 vs. 1.89) in these polymers. Recently, SI-ATRP was also employed to prepare surface quaternized starch nanoparticles for the removal of heavy metals in waste water (Su et al., 2020). In this report, poly(dimethylaminoethyl methacrylate) was first grafted from the surface of starch nanoparticles with CuBr/2,2′-bipyridine as the catalyst in water and then quaternized with methyl groups.

To get a high graft density, Wang et al. prepared a starch-based macroinitiator in ionic liquid ([AMIM]Cl) and then grafted that with PS

and PMMA respectively (Wang, Shen et al., 2015). Compared with products from SI-ATRP, it was reported that both the graft density and ratio were significantly improved because of the homogeneous reaction condition in preparing macroinitiator. Recently, water-soluble waxy potato starch-based macroinitiator was also homogeneously prepared in DMAc/LiCl then the controlled grafting of with acrylamide (AM) and *N*-isopropylacrylamide (NIPAM) was carried out via aqueous Cu°-mediated LRP (Fan, Boulif, & Picchioni, 2018; Fan, Cao, van Mastrigt, Pei, & Picchioni, 2018). In contrast to conventional ATRP, copper (either generated from the disproportionation of CuBr in water or fine powder that directly added to the system) instead of CuBr was used as the catalyst in Cu°-mediated LRP. This method was proved to be more effective for controlled polymerization in the aqueous system (Gavrilov, Zerk, Bernhardt, Percec, & Monteiro, 2016; Zhang, Wilson et al., 2013). In the reported synthesis of starch-g-polyacrylamide (St-g-PAM) via aqueous Cu°-mediated LRP, copper particle from the in-situ disproportionation of CuBr was used as catalyst and monomer conversion ranges from 25 % to 66 % with corresponding polymer chain length (degree of polymerization, DP) in the range of 200 to 600 could be obtained within two hours (Fan, Cao et al., 2018). However, the in-situ generated copper didn't work when targeting polymers with higher DP. Fine copper powder that directly added to the reaction system, on the contrary, was proved to be an effective catalyst, although reasons are still unknown, in another report for the synthesizing of starch-g-poly (acrylamide-co-*N*-isopropylacrylamide) (St-g-(PAM-co-PNIPAM)) with DP around 5000 (Fan, Boulif et al., 2018).

As mentioned earlier, starches that modified by the ATRP method are potential candidates for drug carriers and so on. However, the biotoxicity of the commonly used copper catalyst is one of the problems that hinder their practical applications. Several techniques have been developed for decreasing the concentration of Cu(I) used for polymerization as well as the residues in final products (Aggarwal, 2010; Matyjaszewski, 2012; Wang & Matyjaszewski, 2010). Among them, two reports seem to have significant meaning for eliminating the influence of monovalent copper ions. One was reported by Wang et al., in the research of whose MMA was polymerized with $FeBr_2$ as the catalyst and no ligand was needed (Wang & Matyjaszewski, 2010). In contrast with traditional ATRP, their experiments were successfully carried out in several polar solvents (*N*-methyl-2-pyrrolidone, DMF and acetonitrile), which were believed to act as ligands for the dissolution of $FeBr_2$ and thus the polymerization could be controlled. One should note that, however, too strong coordination between solvent and Fe could lead to failure in controlling the polymerization. In another research reported by Aggarwal, the technique named as supported aqueous-phase catalysis (SAPC) for activator generated by electron transfer (AGET) ATRP was developed (Aggarwal, 2010). *N,N,N',N',N"*-pentamethyldiethylenetriamine (PMDETA) was used as ligand and its complex with $CuBr_2$ was loaded onto various inorganic (for example Na-Clay) and organic materials (starch and cellulose). The performance of SAPC AGET ATRP in polymerization and its ability in controlling the monovalent copper ions in final products were tested by the synthesis of linear poly(benzyl methacrylate) (PBnMA) and PMMA. Catalyst-free polymers were obtained with narrow PDI in the research, which could be taken as effective proofs for the success of the technique. What's more, branched/star PBnMA was also successfully synthesized in his later studies, which reflected the development potential of SAPC AGET ATRP in wide areas.

2.2.2. RAFT and NMP

Although RAFT-mediated polymerization has advantages in preparing metal-free polymers with tailor-made structures and many research have been done on its application in the modification of cellulose and chitosan (Hufendiek, Trouillet, Meier, & Barner-Kowollik, 2014; Semsarilar & Perrier, 2010; Zhang, Wang et al., 2013), only a handful of papers were found to be related to the modification of starch by this technique (see example in Fig. 6). This may be attributed to the following two reasons: the procedure is more complex than ATRP, most of the chain transfer agents are unavailable as commercial products.

In the research carried out by Lu et al., starch-based CTA was synthesized for the controlled grafting of poly(vinyl acetate) (starch-g-PVAc) with AIBN as initiator and starch-g-poly(vinyl alcohol) (starch-g-PVA) was also prepared as derivative (Lu, Xiao, & Sun, 2012; Lu, Xiao, Xu, & Ye, 2011). It is interesting to notice that starch-g-PVAc showed the ability to self-assemble into micelles when mixed with water, while starch-g-PVA could physically crosslink into a hydrogel. All these properties were found to depend on the length of grafted chains that could be well controlled with a narrow PDI (around 1.2).

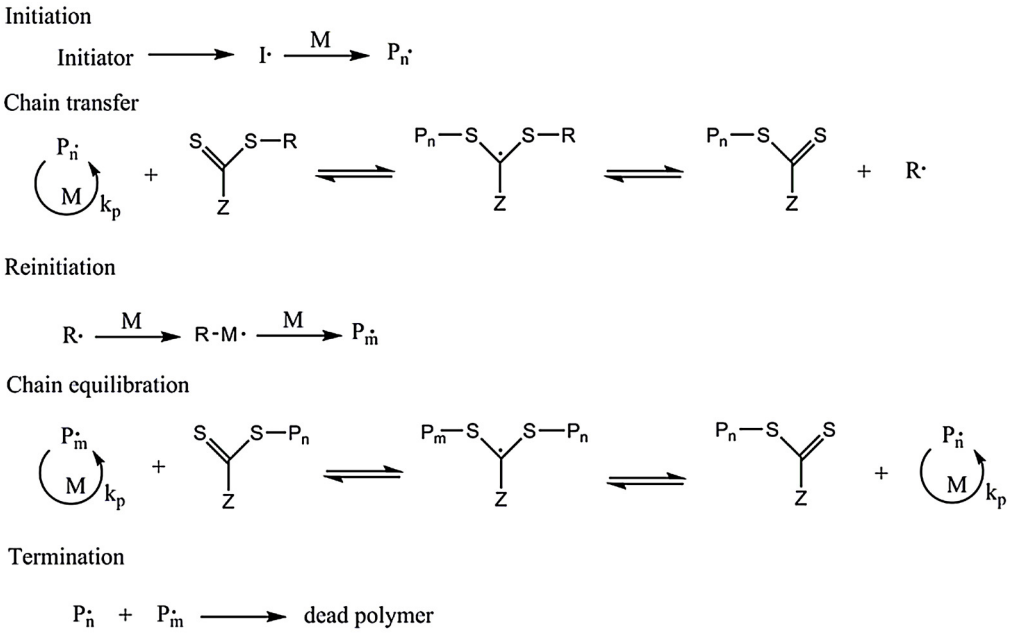
Compared with RAFT, there is much less report on the application of NMP in the modification of starch. As far as we know, the only reported research on the modification of starch via NMP was carried out by Cazotti et al. (Cazotti et al., 2020, 2019). In their work, the surface of starch nanoparticles (SNP) was modified with reactive vinyl groups for the introduction of NMP initiating groups. Afterwards, PS, PMMA, poly (methyl acrylate) (PMA), and poly(acrylic acid) (PAA) were grafted from the SNP surface respectively at different temperatures (90–120 °C) in DMSO. Except for this report, most of the researches on the NMP grafting of polysaccharides focused on macromolecules such as cellulose, chitosan, and guar gum (García-Valdez, Champagne-Hartley, Saldívar-Guerra, Champagne, & Cunningham, 2015; Glasing, Bouchard, Jessop, Champagne, & Cunningham, 2017; Holmes, 2007; Karaj-Abad, Abbasian, & Jaymand, 2016; Moreira et al., 2015).

2.2.3. Click chemistry

The introduction of "click" chemistry to polymer science opened up a new way to synthesize various polymers with well-defined structures, especially when this was combined with controlled/living radical polymerization techniques like ATRP and so on. Reviews on different techniques that use "click" reaction to prepare polymers and various clickable initiators, monomers and polymers are available in recent years (2014, Hoogenboom, 2010; Huang, Qin, & Tang, 2018; Lowe, 2010; Mansfeld, Pietsch, Hoogenboom, Becer, & Schubert, 2010; Tasdelen, 2011).

When used for the modification of starch, one commonly employed "click" reaction is copper-catalyzed [3 + 2] Huisgen cycloaddition reaction (CuAAC) (Fig. 7). With this method, oligocaprolactone was grafted onto soluble starch in the research of Uliniuc et al. and amphiphilic copolymer was obtained via tuning the chain length of oligocaprolactone (Uliniuc et al., 2013). This amphiphilic starch-based copolymer was proved able to form micelles in water at low concentration, which renders it a potential candidate for applications like controlled drug delivery. In another report, covalently crosslinked Kraft pulp-starch composite was prepared via CuAAC and significantly enhanced mechanical properties were observed after the crosslink (Elchinger, Awada, Zerrouki, Montplaisir, & Zerrouki, 2014). Besides using CuAAC alone, reports on the combination of CuAAC with ATRP, RAFT, ROP and enzymatic method in the grafting of starches are available in recent years. In one research carried out by Bertoldo et al., homopolymers of methacrylate, butyl acrylate, and dimethylaminoethyl methacrylate synthesized via ATRP were "click" onto amylose separately (Bertoldo, Zampano, Terra, & Castelvetro, 2011). The reported method for functionalizing starch with alkynyl groups, in which the AGU was oxidized by sodium periodate to generate aldehyde groups and then reduced with propargylamine/sodium cyanoborohydride (see Fig. 7), could be easily and efficiently carried out in mild reaction conditions. However, the yield of this method still needs to be improved. In another report, amylose-graft-poly(n-butyl methacrylate) (Am-g-PBMA) was successfully synthesized through the combination of ATRP and CuAAC (Borsacchi et al., 2014). Subsequent Electron paramagnetic resonance (EPR) analysis revealed the presence of residual Cu (II) after the extensive purification process. The total amount of residual Cu(II) which existed in three different forms (coordinate with ligands, coordinate with triazole nitrogens and Cu(II) cluster) was calculated to be about 7 % of that introduced as catalyst. The last two forms of Cu(II)

Reaction mechanism of RAFT



Example of RAFT grafting

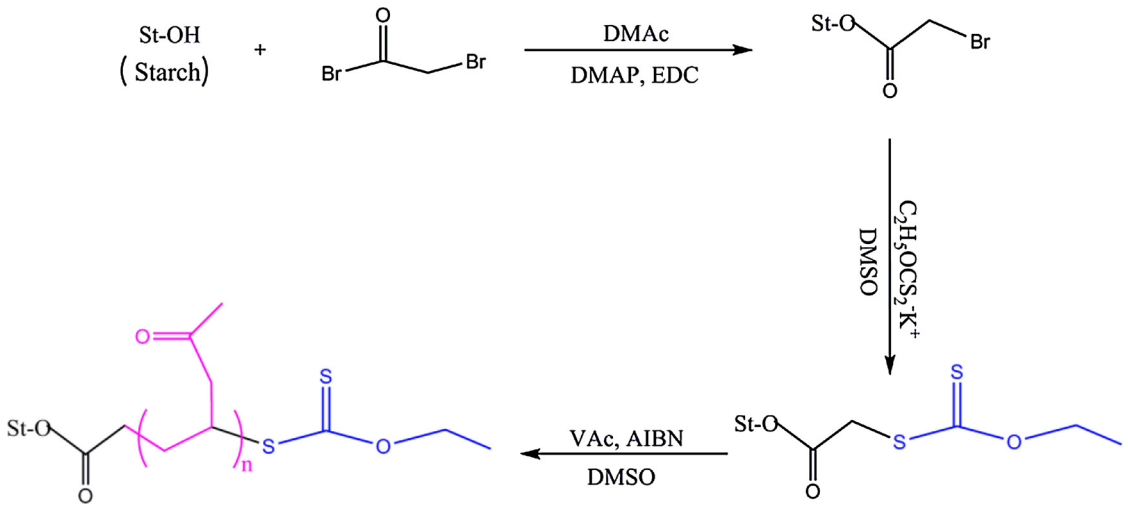


Fig. 6. The reaction mechanism for RAFT and an example of its application in starch modification.

were believed to be difficult to be removed through prolonged dialysis. This may hinder the practical application of CuAAC in the production of biocompatible materials. Compared with ATRP, reports on the combination of CuAAC with RAFT and ROP is relatively fewer (Karami Ghaleseiedi, Dadkhah Tehrani, & Parsamanesh, 2018; Xiao, Lu, Xu, & Huang, 2011).

Besides CuAAC, the thiol-ene "click" reaction was also reported for synthesizing starch-based materials. One example is the synthesis of starch-based hydrogel for cell encapsulation (Dong et al., 2016). In this research, sulfobetaine functionalized starch acrylate could be rapidly and conveniently crosslinked with dithiol-functionalized poly(ethylene glycol) under physiological conditions. The obtained biodegradable antifouling hydrogel possibly could be a good candidate for 3D cell encapsulation and culture in vitro. In another report, corn starch was functionalized with allyl chloride and *L*-Cysteine respectively and hydrogel can be obtained via simply mixing these two modified starches (Li, Tan, Xu, Lu, & Wang, 2017). With good mechanical and biodegradable properties, this hydrogel could be a promising material for tissue engineering. In addition to hydrogels, light-mediated thiol-ene "click" was also employed for the preparation of macroporous peptide-immobilized antimicrobial starch sponges (Yang et al., 2019). Potato starch was first esterified with norbornene anhydride in DMSO and sponge was prepared subsequently via the lyophilization of starch hydrogel that obtained from the dithiol-functionalized poly(ethylene glycol) photocrosslinking. An antimicrobial peptide with thiol group was then immobilized on the sponge via the thio-ene photoreaction. The obtained biodegradable sponge displayed good hemostatic and antimicrobial performance.

Another "click" reaction for the modification of starch recently reported is Diels-Alder reaction. For example, this reaction was combined

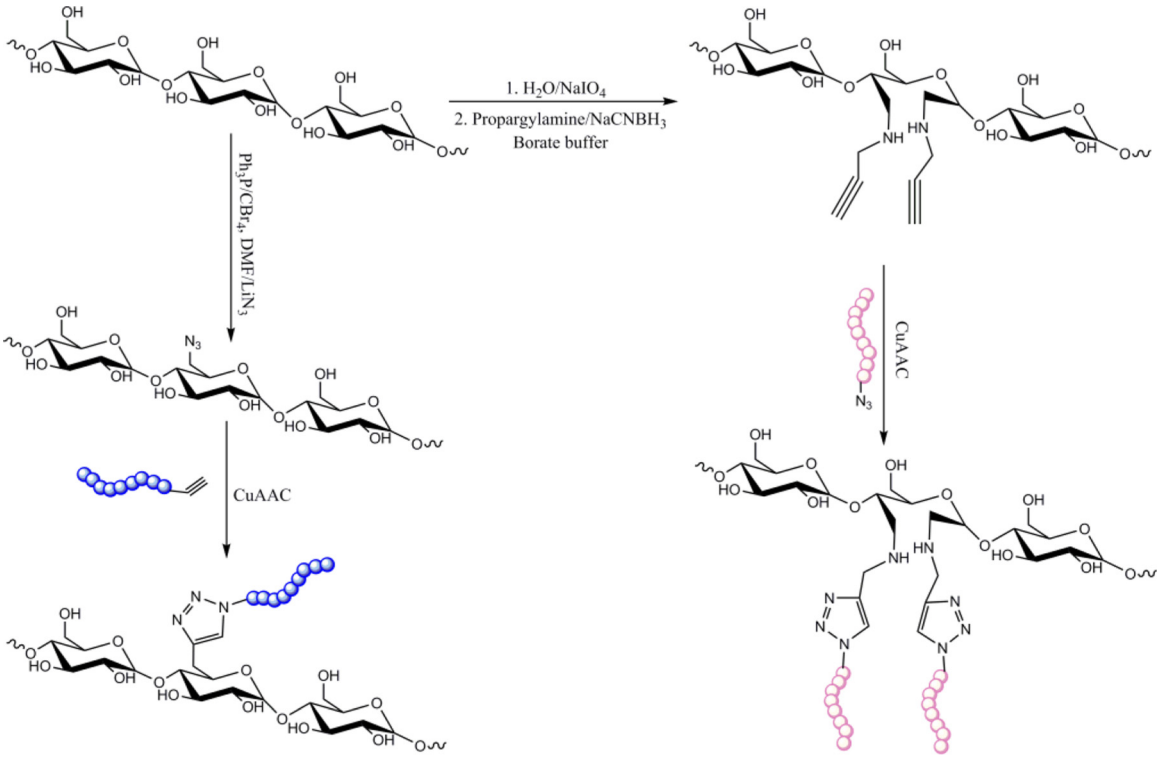


Fig. 7. "Click" reaction scheme for starch modification.

with organocatalytic transesterification for the synthesis of starch-farnesene bio-renewable polymer (Orzolek, Rahman, & Iovine, 2018). Trans-β-farnesene, an acyclic sesquiterpene hydrophobic building block that is produced through a sustainable large-scale fermentation process, was employed as both diene and solvent for Diels-Alder reaction to introduce ester group for the following modification of starch. 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) was used as an organocatalyst for the homogeneous transesterification reaction in DMSO to obtain modified starch with DS from 0.3 to 2.6. The results suggest that linear amylose is more favorable for the organocatalytic transesterification than branched amylopectin due to their difference in molecular structure. This method paves a new way to modify polysaccharides. What's more, the double bond in farnesene can be kept intact after transesterification, thus potentially can be used for further modification like thiol-ene reaction. In Gabilondo's group, starch was functionalized with furfuryl isocyanate and then cross-linked with water-soluble polypropylene glycol-block-polyethylene glycol-block-polypropylene glycol-based bismaleimide and polyethylene glycol-based tetramaleimide respectively (González et al., 2018, 2019). Graphene sheets and cellulose nanocrystals (CNC) were added separately to obtain hydrogels with properties like antimicrobial activity, conductivity or improved macroporous structure for drug delivery.

2.2.4. Chemo-enzymatic modification

Various enzymes have been discovered and employed for the processing of starches in the past few decades. For example, amylases are used to hydrolyze starches into small molecules like maltose and glucose, while α-glucanotransferases (AGTases) are useful for remodeling the molecular structures of starches. The properties and applications of microbial AGTases in the modification of starches have been kindly reviewed by van der Maarel et al. and as illustrated in their paper varieties of derivatives could be achieved by this treatment (van der Maarel & Leemhuis, 2013).

Although amylose, which has a helical conformation thus is expected to act as a good host molecule for the preparation of functional materials, could also be prepared by AGTases, one of the most effective ways to get the pure product is considered to be α-glucan phosphorylase (GP) catalyzed α-D-glucose 1-phosphate (G-1-P) polymerization (Kadokawa, 2014). Maltooligosaccharides, the DS of which should be large enough to be recognized by GP, are needed as a primer to initiate the polymerization. Take potato GP catalyzed polymerization as an example, maltotetraose is usually employed as the primer and the chain will propagate at the nonreducing end of the primer in a step-growth manner. Hence, this process could be taken as a living polymerization and the molecular weight of resultant amylose can be tailored by varying the molar ratio of G-1-P to primer while the PDI could be controlled within 1.2 (Kadokawa, 2014). The application of this technique in the preparation of functional polymers can be seen in the review composed by Kadokawa (Kadokawa, 2014). As implied by this review and other reports, amylose has been successfully grafted to many other polysaccharides like alginate, chitosan, and cellulose by combining GP catalyzed polymerization with certain chemical reactions (chemoenzymatic approach) (Kadokawa, Arimura, Takemoto, & Yamamoto, 2012; Kadokawa, Egashira, & Yamamoto, 2018; Omagari, Kaneko, & Kadokawa, 2010). Besides grafting, amylose block copolymers were also successfully synthesized in recent years. One example is the synthesis of poly(2-vinyl pyridine)-b-amylose (P2VP-b-amylose) which generates a copolymer with rod-coil structure (Kumar, Woortman, & Loos, 2015). In this research, maltoheptaose lactone was reacted with amino-terminated P_2VP and then GP catalyzed polymerization was carried out. The obtained copolymer is expected to possess both the inclusion ability from amylose due to its helical conformation with a hydrophobic cavity within the helix and the intermolecular complexation ability from P_2VP due to the strong hydrogen bond, therefore, should be a good candidate for the fabrication of self-assembly materials. Another method for the preparation of functional supramolecular materials with amylose as host molecules is the so-called "vine-twining polymerization" (Kadokawa, Tanaka, Hatanaka, & Yamamoto, 2015). According to this method, GP catalyzed polymerization is carried out in a dispersion solution of appropriate hydrophobic polymer. The hydrophobic polymer "rod" will be included in the cavity of the synthesized amylose helix. Several hydrogels were

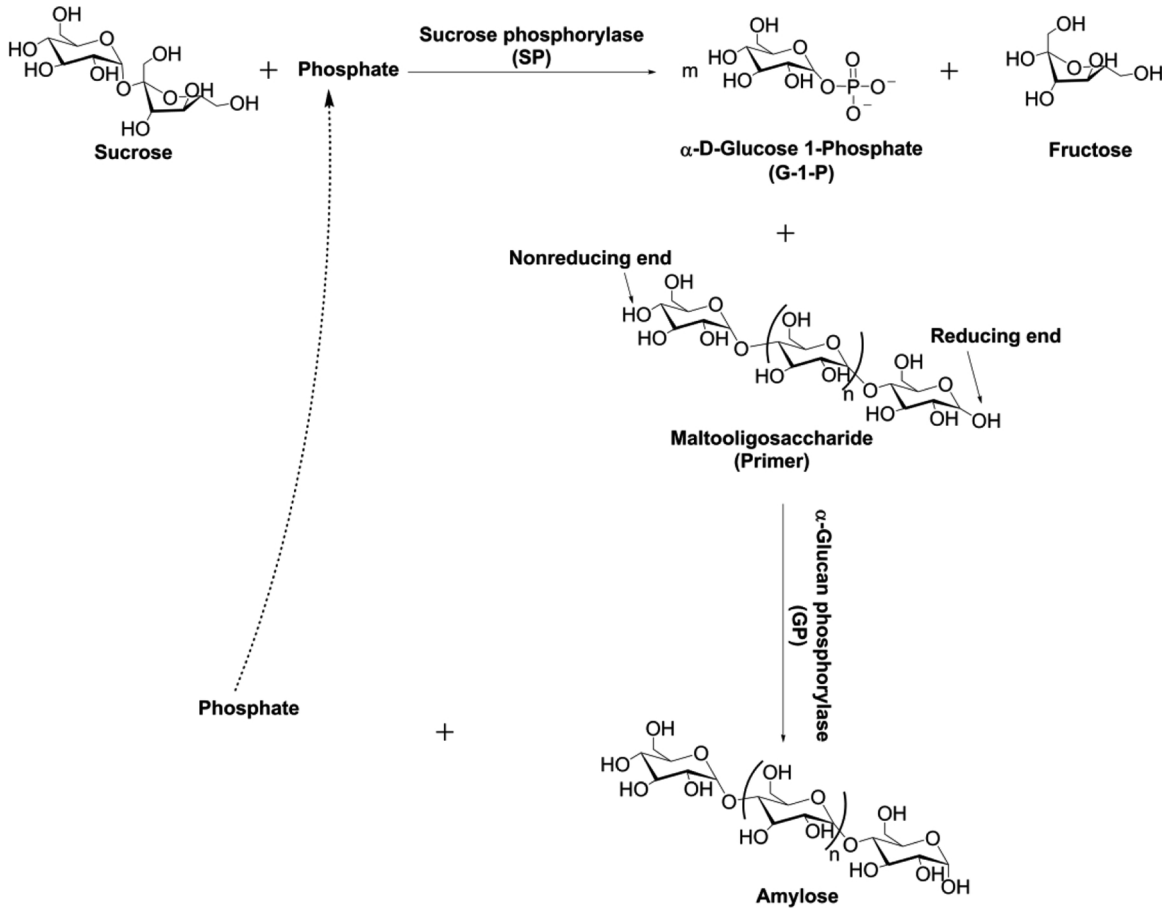


Fig. 8. One-pot enzymatic synthesis of amylose from sucrose.

synthesized via this method and review on this now is available (Orio, Yamamoto, & Kadokawa, 2017; Tanaka et al., 2015).

In addition to the materials mentioned above, this chemoenzymatic approach has also been employed to modify the surfaces of different materials to prevent biofouling. For instance, potato phosphorylase was tested by van der Vlist et al. for the grafting of amylose brushes from the surface of silicon and *Deinococcus geothermalis branching enzyme* was then employed for the preparation of hyperbranched polysaccharide surface coating (van der Vlist, Schonen, & Loos, 2011). Results from X-ray photoelectron spectroscopy (XPS) and spectroscopic ellipsometry revealed the successful grafting of both linear and hyperbranched brushes. A similar method was also used by Mazzocchetti et al. to graft amylose brushes from the surfaces of Si and Au, in which experiment 3-aminopropyldimethyethoxysilane (APDMES) and cystamine were used respectively for the amination of the two different surfaces and then maltoheptaoses were immobilized onto the surfaces as primers to initiate polymerization (Mazzocchetti, Tsoufis, Rudolf, & Loos, 2014). Phosphorylases from rabbit muscles and potatoes were studied for the catalytic polymerization of G-1-P and it was reported that amylose brushes synthesized by rabbit muscle phosphorylases showed a better performance in preventing protein adsorption.

Despite all the advantages brought by GP catalyzed polymerization, there are still some problems faced by the industrialization of this approach. For example, the monomer used in this approach, G-1-P, is too expensive and the commonly used potato phosphorylase is not thermostable enough for practical application. Numerous research has been done to overcome these problems and these could be seen in the review composed by Ohdan (Ohdan, Fujii, Yanase, Takaha, & Kuriki, 2006). According to this article and other reports, the most suitable method available by now for the synthesis of amylose is the combining use of sucrose phosphorylase (SP) with GP in the presence of inorganic phosphate with sucrose as substrate. G-1-P, produced as the result of the SP catalyzed phosphorolysis of sucrose, was used as the substrate for GP catalyzed polymerization (Fig. 8) (Doblado-Maldonado, Gomand, Goderis, & Delcour, 2017; Qi, You, & Zhang, 2014; Waldmann, Gygax, Bednarski, Randall Shangraw, & Whitesides, 1986). Results showed that amylose can be obtained with a higher yield than directly synthesized from G-1-P. The molecular weight of amylose from this method could also be controlled by varying the molar ratio of sucrose to primer and the PDI was found to be about 1. However, no report has been found by now on the application of this method in the preparation of functional materials as that synthesized from GP catalyzed polymerization of G-1-P.

3. Conclusions

With the development of technology and society, increasing attention is being paid to the utilization of polysaccharides such as starch to reduce the reliance on fossil fuel that is nonrenewable. Starch, as a kind of widely existed renewable polysaccharide, has been modified for the applications in various areas that are now being extended gradually with the development of polymer science and technology. However, although megatons of starch derivatives are produced and consumed every year, the conventional way in which they are modified is still not eco-friendly enough to reduce the environmental impact (wastewater, toxic organic solvent). What's more, most of the starch products are low value-added and their performance is far from excellent for application, which means in some cases large amounts of them have to be used to achieve desirable properties. Thus, nowadays more focus is being paid to the development of new techniques that could produce "high-

performance" starch derivatives in a "green" way. In the past decades, one interesting progress in the modification of starch is the introduction of "green" solvents such as ionic liquids (ILs) and supercritical CO_2 ($scCO_2$) for the modification of starch. Not only could ILs serve as reaction medium, in some cases, they can also catalyze the chemical reaction or act as a better plasticizer than traditional ones such as glycerol. Success was also obtained when using $scCO_2$ as the solvent for the modification of starch, in both physical (gelatinization, extrusion, foaming, and impregnation) and chemical (esterification and grafting) ways.

While the introduction of "green" solvents provides us the possibilities to prepare desirable products without the significant environmental impact that caused by the use of organic solvents in traditional methods, controlled modification (regioselective functionalization of hydroxyl groups and controlled grafting) of starch makes it possible to obtain starch derivatives with tailor-made properties. Generally, regioselective functionalization could be achieved by three different methods, which are the protection-deprotection approach, catalyzed functionalization and site-selective replacement of OH-groups respectively. In these methods, regioselectivity is related to steric hindrance or supramolecular structure formed in specific solvents. As for controlled grafting, methods like ATRP, Cu^0-mediated LRP, RAFT, click reaction and chemo-enzymatic approach are already available.

In the future, the combination of these methods could be of interest for the preparation of high value-added starch-based materials in a green and efficient way. Although there is still lots of work to be done, it is clear that the development and application of starch-based materials could benefit significantly from the progress of "green" solvent and controlled modification. The same is true for the sustainable development of human society.

Acknowledgments

This work was finished under the financial support from China Scholarship Council (CSC) with the Grant Number 201406380107. We thank Dr. Laurens Polgar and Dr. Patrizio Raffa for proofreading.

References

Aggarwal, R. (2010). *Supported aqueous-phase catalysis for atom transfer radical polymerization.* PhD dissertationUniversity of Tennessee.

Ai, Y., & Jane, J.-l. (2015). Gelatinization and rheological properties of starch. *Starch - Stärke, 67*(3–4), 213–224.

Alfaifi, A. Y., El-Newehy, M. H., Abdel-Halim, E. S., & Al-Deyab, S. S. (2014). Microwave-assisted graft copolymerization of amino acid based monomers onto starch and their use as drug carriers. *Carbohydrate Polymers, 106*, 440–452.

Anastasaki, A., Nikolaou, V., Nurumbetov, G., Wilson, P., Kempe, K., Quinn, J. F., & Haddleton, D. M. (2016). Cu(0)-mediated living radical polymerization: A versatile tool for materials synthesis. *Chemical Reviews, 116*(3), 835–877.

Ashogbon, A. O., & Akintayo, E. T. (2014). Recent trend in the physical and chemical modification of starches from different botanical sources: A review. *Starch - Stärke, 66*(1–2), 41–57.

Avval, M. E., Moghaddam, P. N., & Fareghi, A. R. (2013). Modification of starch by graft copolymerization: A drug delivery system tested for cephalexin antibiotic. *Starch - Stärke, 65*(7–8), 572–583.

Ayoub, A., & Rizvi, S. S. H. (2008). Properties of supercritical fluid extrusion-based crosslinked starch extrudates. *Journal of Applied Polymer Science, 107*(6), 3663–3671.

Ayoub, A., & Rizvi, S. S. H. (2011). Reactive supercritical fluid extrusion for development of moisture resistant starch-based foams. *Journal of Applied Polymer Science, 120*(4), 2242–2250.

Barsi, D., Borsacchi, S., Calucci, L., Tarantino, A., Pinzino, C., & Bertoldo, M. (2017). Tuning the functionalization degree of amylose and amylopectin with photochromic spiropyran by CuAAc reaction. *Polymer, 120*, 82–93.

Benavent-Gil, Y., & Rosell, C. M. (2017). Comparison of porous starches obtained from different enzyme types and levels. *Carbohydrate Polymers, 157*, 533–540.

Bertoft, E., & Blennow, A. (2016). *Structure of potato starchAdvances in potato chemistry and technology* (Second edition). Elsevier57–73.

Bertoldo, M., Zampano, G., Terra, F. L., & Castelvetro, V. (2011). Amphiphilic amylose-g-poly(meth)acrylate copolymers through "click" onto grafting method. *Biomacromolecules, 12*(2), 388–398.

Borsacchi, S., Calucci, L., Geppi, M., La Terra, F., Pinzino, C., & Bertoldo, M. (2014). Characterization of an amylose-graft-poly(n-butyl methacrylate) copolymer obtained by click chemistry by EPR and SS-NMR spectroscopies. *Carbohydrate Polymers, 112*, 245–254.

Boyer, C., Corrigan, N. A., Jung, K., Nguyen, D., Nguyen, T. K., Adnan, N. N., & Yeow, J. (2016). Copper-mediated living radical polymerization (Atom transfer radical polymerization and copper(0) mediated polymerization): From fundamentals to bioapplications. *Chemical Reviews, 116*(4), 1803–1949.

Bragd, P. L., Besemer, A. C., & van Bekkum, H. (2000). Bromide-free TEMPO-mediated oxidation of primary alcohol groups in starch and methyl α-d-glucopyranoside. *Carbohydrate Research, 328*(3), 355–363.

Bruno, F. F., Akkara, J. A., Ayyagari, M., Kaplan, D. L., Gross, R., Swift, G., ... Dordick, J. S. (1995). Enzymic modification of insoluble amylose in organic solvents. *Macromolecules, 28*(26), 8881–8883.

Cao, C., Nian, B., Li, Y., Wu, S., & Liu, Y. (2019). Multiple hydrogen-bonding interactions enhance the solubility of starch in natural deep eutectic solvents: Molecule and macroscopic scale insights. *Journal of Agricultural and Food Chemistry, 67*(45), 12366–12373.

Carlstedt, J., Wojtasz, J., Fyhr, P., & Kocherbitov, V. (2015). Understanding starch gelatinization: The phase diagram approach. *Carbohydrate Polymers, 129*, 62–69.

Cazotti, J. C., Fritz, A. T., Garcia-Valdez, O., Smeets, N. M. B., Dube, M. A., & Cunningham, M. F. (2019). Grafting from starch nanoparticles with synthetic polymers via nitroxide-mediated polymerization. *Macromolecular Rapid Communications*e1800834.

Cazotti, J. C., Fritz, A. T., Garcia-Valdez, O., Smeets, N. M., Dubé, M. A., & Cunningham, M. F. (2020). Graft modification of starch nanoparticles using nitroxide-mediated polymerization and the grafting from approach. *Carbohydrate Polymers, 228*, 115384.

Chakraborty, S., Sahoo, B., Teraoka, I., Miller, L. M., & Gross, R. A. (2005). Enzyme-catalyzed regioselective modification of starch nanoparticles. *Macromolecules, 38*(1), 61–68.

Chakraborty, S., Jähnichen, K., Komber, H., Basfar, A. A., & Voit, B. (2014). Synthesis of magnetic polystyrene nanoparticles using amphiphilic ionic liquid stabilized RAFT mediated miniemulsion polymerization. *Macromolecules, 47*(13), 4186–4198.

Chang, P. S., & Robyt, J. F. (1996). Oxidation of primary alcohol groups of naturally occurring polysaccharides with 2,2,6,6-Tetramethyl-1-Piperidine oxoammonium ion. *Journal of Carbohydrate Chemistry, 15*(7), 819–830.

Chen, K. H., & Rizvi, S. S. H. (2006). Rheology and expansion of starch-water-CO_2 mixtures with controlled gelatinization by supercritical fluid extrusion. *International Journal of Food Properties, 9*(4), 863–876.

Chen, Q., Yu, H., Wang, L., ul Abdin, Z., Chen, Y., Wang, J., ... Zhang, H. (2015). Recent progress in chemical modification of starch and its applications. *RSC Advances, 5*(83), 67459–67474.

Chen, J., Xie, F., Li, X., & Chen, L. (2018). Ionic liquids for the preparation of biopolymer materials for drug/gene delivery: A review. *Green Chemistry, 20*(18), 4169–4200.

Cimecioglu, A., Ball, D., Kaplan, D., & Huang, S. (1994). Preparation of amylose derivatives selectively modified at C-6. 6-Amino-6-deoxyamylose. *Macromolecules, 27*(11), 2917–2922.

Cimecioglu, A. L., Ball, D. H., Huang, S. H., & Kaplan, D. L. (1997). A direct regioselective route to 6-azido-6-deoxy polysaccharides under mild and homogeneous conditions. *Macromolecules, 30*(1), 155–156.

Clode, D., & Horton, D. (1971). Preparation and characterization of the 6-aldehydo derivatives of amylose and whole starch. *Carbohydrate Research, 17*(2), 365–373.

Comin, L. M., Temelli, F., & Saldaña, M. D. A. (2012). Impregnation of flax oil in pregelatinized corn starch using supercritical CO_2. *The Journal of Supercritical Fluids, 61*, 221–228.

Cumpstey, I. (2013). Chemical modification of polysaccharides. *ISRN Organic Chemistry, 2013*, 417672.

Dai, Y., van Spronsen, J., Witkamp, G. J., Verpoorte, R., & Choi, Y. H. (2013). Natural deep eutectic solvents as new potential media for green technology. *Analytica Chimica Acta, 766*, 61–68.

de Aguiar, A. C., Sales, L. P., Coutinho, J. P., Barbero, G. F., Godoy, H. T., & Martínez, J. (2013). Supercritical carbon dioxide extraction of Capsicum peppers: Global yield and capsaicinoid content. *The Journal of Supercritical Fluids, 81*, 210–216.

De Marco, I., Riemma, S., & Iannone, R. (2018). Life cycle assessment of supercritical CO 2 extraction of caffeine from coffee beans. *The Journal of Supercritical Fluids, 133*, 393–400.

de Souza, A. C., Dias, A. M. A., Sousa, H. C., & Tadini, C. C. (2014). Impregnation of cinnamaldehyde into cassava starch biocomposite films using supercritical fluid technology for the development of food active packaging. *Carbohydrate Polymers, 102*, 830–837.

Desalegn, T., Garcia, I. J. V., Titman, J., Licence, P., & Chebude, Y. (2014). Synthesis of starch vernolate in 1-butyl-3-methylimidazolium chloride ionic liquid. *Starch - Stärke, 67*, 200–203.

Dias, F. T. G., Souza, R. R., & Lucas, E. F. (2015). Influence of modified starches composition on their performance as fluid loss additives in invert-emulsion drilling fluids. *Fuel, 140*, 711–716.

Dicke, R. (2004). A straight way to regioselectively functionalized polysaccharide esters. *Cellulose, 11*(2), 255–263.

Dicke, R., Rahn, K., Haack, V., & Heinze, T. (2001). Starch derivatives of high degree of functionalization. Part 2. Determination of the functionalization pattern of *p*-toluenesulfonyl starch by peracylation and NMR spectroscopy. *Carbohydrate Polymers, 45*(1), 43–51.

Ding, M., Jiang, X., Zhang, L., Cheng, Z., & Zhu, X. (2015). Recent progress on transition metal catalyst separation and recycling in ATRP. *Macromolecular Rapid Communications, 36*(19), 1702–1721.

Doblado-Maldonado, A. F., Gomand, S. V., Goderis, B., & Delcour, J. A. (2017). Methodologies for producing amylose: A review. *Critical Reviews in Food Science and Nutrition, 57*(2), 407–417.

Dong, D., Li, J., Cui, M., Wang, J., Zhou, Y., Luo, L., & Yao, F. (2016). In situ "Clickable" zwitterionic starch-based hydrogel for 3D cell encapsulation. *ACS Applied Materials &*

Interfaces, 8(7), 4442–4455.
Dragan, E. S., Apopei Loghin, D. F., & Cocarta, A. I. (2014). Efficient sorption of Cu(2+) by composite chelating sorbents based on potato starch-graft-polyamidoxime embedded in chitosan beads. *ACS Applied Materials & Interfaces, 6*(19), 16577–16592.
Druel, L., Bardl, R., Vorwerg, W., & Budtova, T. (2017). Starch aerogels: A member of the family of thermal superinsulating materials. *Biomacromolecules, 18*(12), 4232–4239.
Duarte, A. R. C., Mano, J. F., & Reis, R. L. (2009). Preparation of starch-based scaffolds for tissue engineering by supercritical immersion precipitation. *The Journal of Supercritical Fluids, 49*(2), 279–285.
Einfeldt, L., Petzold, K., Günther, W., Stein, A., Kussler, M., & Klemm, D. (2001). Preparative and 1H-NMR investigation on regioselective silylation of starch dissolved in dimethyl sulfoxide. *Macromolecule Bioscience, 1*(8), 341–347.
Elchinger, P.-H., Awada, H., Zerrouki, C., Montplaisir, D., & Zerrouki, R. (2014). Kraft pulp–Starch covalent linking: A promising route to a new material. *Industrial & Engineering Chemistry Research, 53*(18), 7604–7610.
Fan, Y., Boulif, N., & Picchioni, F. (2018). Thermo-responsive Starch-g-(PAM-co-PNIPAM): Controlled synthesis and effect of molecular components on solution rheology. *Polymers, 10*(1), 92.
Fan, Y., Cao, H., van Mastrigt, F., Pei, Y., & Picchioni, F. (2018). Copper-mediated homogeneous living radical polymerization of acrylamide with waxy potato starch-based macroinitiator. *Carbohydrate Polymers, 192*, 61–68.
Francisco, J. C., & Sivik, B. (2002). Gelatinization of cassava, potato and wheat starches in supercritical carbon dioxide. *The Journal of Supercritical Fluids, 22*, 247–254.
Gao, J., Luo, Z. G., & Luo, F. X. (2012). Ionic liquids as solvents for dissolution of corn starch and homogeneous synthesis of fatty-acid starch esters without catalysts. *Carbohydrate Polymers, 89*(4), 1215–1221.
Gao, C., Liu, S., & Edgar, K. J. (2018). Regioselective chlorination of cellulose esters by methanesulfonyl chloride. *Carbohydrate Polymers, 193*, 108–118.
García-Valdez, O., Champagne-Hartley, R., Saldívar-Guerra, E., Champagne, P., & Cunningham, M. F. (2015). Modification of chitosan with polystyrene and poly(n-butyl acrylate) via nitroxide-mediated polymerization and grafting from approach in homogeneous media. *Polymer Chemistry, 6*(15), 2827–2836.
Gavrilov, M., Zerk, T. J., Bernhardt, P. V., Percec, V., & Monteiro, M. J. (2016). SET-LRP of NIPAM in water via in situ reduction of Cu(II) to Cu(0) with NaBH4. *Polymer Chemistry, 7*(4), 933–939.
Glasing, J., Bouchard, J., Jessop, P. G., Champagne, P., & Cunningham, M. F. (2017). Grafting well-defined CO2-responsive polymers to cellulose nanocrystals via nitroxide-mediated polymerisation: Effect of graft density and molecular weight on dispersion behaviour. *Polymer Chemistry, 8*(38), 6000–6012.
González, K., García-Astrain, C., Santamaria-Echart, A., Ugarte, L., Avérous, L., Eceiza, A., ... Gabilondo, N. (2018). Starch/graphene hydrogels via click chemistry with relevant electrical and antibacterial properties. *Carbohydrate Polymers, 202*, 372–381.
González, K., Guaresti, O., Palomares, T., Alonso-Varona, A., Eceiza, A., & Gabilondo, N. (2019). The role of cellulose nanocrystals in biocompatible starch-based clicked nanocomposite hydrogels. *International Journal of Biological Macromolecules*.
Halley, P., & Avérous, L. (2014). *Starch polymers-from genetic engineering to green applications*.
Hampe, R., & Heinze, T. (2014). Studies about the solvent-dependent substitution pattern of starch acetates. *Macromolecular Materials and Engineering, 299*(10), 1188–1196.
He, W., Jiang, H., Zhang, L., Cheng, Z., & Zhu, X. (2013). Atom transfer radical polymerization of hydrophilic monomers and its applications. *Polymer Chemistry, 4*(10), 2919.
Ho, S. H., Ye, X., Hasunuma, T., Chang, J. S., & Kondo, A. (2014). Perspectives on engineering strategies for improving biofuel production from microalgae -a critical review. *Biotechnology Advances, 32*(8), 1448–1459.
Holmes, V. (2007). *The application of controlled radical polymerization processes on the graft copolymerization of hydrophobic substituents onto guar gum and guar gum derivatives.* PhD dissertationLouisiana State University.
Hoogenboom, R. (2010). Thiol-yne chemistry: A powerful tool for creating highly functional materials. *Angewandte Chemie (International Ed in English), 49*(20), 3415–3417.
Huang, D., Qin, A., & Tang, B. Z. (2018). *Overview of click polymerization. Click polymerization*1–35.
Hufendiek, A., Trouillet, V., Meier, M. A., & Barner-Kowollik, C. (2014). Temperature responsive cellulose-graft-copolymers via cellulose functionalization in an ionic liquid and RAFT polymerization. *Biomacromolecules, 15*(7), 2563–2572.
Kadokawa, J.-i. (2014). Chemoenzymatic synthesis of functional amylosic materials. *Pure and Applied Chemistry, 86*(5).
Kadokawa, J.-i., Arimura, T., Takemoto, Y., & Yamamoto, K. (2012). Self-assembly of amylose-grafted carboxymethyl cellulose. *Carbohydrate Polymers, 90*(3), 1371–1377.
Kadokawa, J.-i., Tanaka, K., Hatanaka, D., & Yamamoto, K. (2015). Preparation of multiformable supramolecular gels through helical complexation by amylose in vine-twining polymerization. *Polymer Chemistry, 6*(35), 6402–6408.
Kadokawa, J. I., Egashira, N., & Yamamoto, K. (2018). Chemoenzymatic preparation of amylose-grafted chitin nanofiber network materials. *Biomacromolecules, 19*(7), 3013–3019.
Karaj-Abad, S. G., Abbasian, M., & Jaymand, M. (2016). Grafting of poly[(methyl methacrylate)-block-styrene] onto cellulose via nitroxide-mediated polymerization, and its polymer/clay nanocomposite. *Carbohydrate Polymers, 152*, 297–305.
Karami Ghaleseiedi, Z., Dadkhah Tehrani, A., & Parsamanesh, M. (2018). Starch-based dual amphiphilic graft copolymer as a new pH-sensitive maltidrug co-delivery system. *International Journal of Biological Macromolecules, 118*(Pt. A), 913–920.
Kärkkäinen, J., Lappalainen, K., Joensuu, P., & Lajunen, M. (2011). HPLC-ELSD analysis of six starch species heat-dispersed in [BMIM]Cl ionic liquid. *Carbohydrate Polymers, 84*(1), 509–516.
Kemmere, M. F., & Meyer, T. (2006). *Supercritical carbon dioxide: In polymer reaction engineering.* John Wiley & Sons.
Klibanov, A. M. (1997). Why are enzymes less active in organic solvents than in water? *Trends in Biotechnology, 15*(3), 97–101.
Klohr, E.-A., Koch, W., Klemm, D., & Dicke, R. (2005). Method of producing regioselectively substituted esters of oligo-and polysaccharides. United States Patent, Patent number: US6852852 B2.
Kubisa, P. (2009). Ionic liquids as solvents for polymerization processes—Progress and challenges. *Progress in Polymer Science, 34*(12), 1333–1347.
Kumar, K., Woortman, A. J., & Loos, K. (2015). Synthesis of amylose-b-P2 VP block copolymers. *Macromolecular Rapid Communications, 36*(23), 2097–2101.
Lappalainen, K., Karkkainen, J., & Lajunen, M. (2013). Dissolution and depolymerization of barley starch in selected ionic liquids. *Carbohydrate Polymers, 93*(1), 89–94.
Lehmann, A., & Volkert, B. (2011). Preparing esters from high-amylose starch using ionic liquids as catalysts. *Carbohydrate Polymers, 83*(4), 1529–1533.
Leroy, E., Decaen, P., Jacquet, P., Coativy, G., Pontoire, B., Reguerre, A.-L., ... Lourdin, D. (2012). Deep eutectic solvents as functional additives for starch based plastics. *Green Chemistry, 14*(11), 3063.
Leroy, E., Jacquet, P., Coativy, G., Reguerre, A. L., & Lourdin, D. (2012). Compatibilization of starch-zein melt processed blends by an ionic liquid used as plasticizer. *Carbohydrate Polymers, 89*(3), 955–963.
Li, K., Liu, H., Gao, W., Chen, M., Zeng, Y., Liu, J., & Wu, D. (2015). Mulberry-like dual-drug complicated nanocarriers assembled with apogossypolone amphiphilic starch micelles and doxorubicin hyaluronic acid nanoparticles for tumor combination and targeted therapy. *Biomaterials, 39*, 131–144.
Li, Y., Tan, Y., Xu, K., Lu, C., & Wang, P. (2017). A biodegradable starch hydrogel synthesized via thiol-ene click chemistry. *Polymer Degradation and Stability, 137*, 75–82.
Liebert, T., Kulicke, W. M., & Heinze, T. (2008). Novel approach towards hydrolytically stable starch acetates for physiological applications. *Reactive & Functional Polymers, 68*(1), 1–11.
Liu, W., & Budtova, T. (2013). Dissolution of unmodified waxy starch in ionic liquid and solution rheological properties. *Carbohydrate Polymers, 93*(1), 199–206.
Liu, P., & Su, Z. (2005). Surface-initiated atom transfer radical polymerization (SI-ATRP) of n-butyl acrylate from starch granules. *Carbohydrate Polymers, 62*(2), 159–163.
Liu, W.-w., Zhang, B., Li, Y.-z., He, Y.-m., & Zhang, H.-c. (2014). An environmentally friendly approach for contaminants removal using supercritical CO2 for re-manufacturing industry. *Applied Surface Science, 292*, 142–148.
Lowe, A. B. (2010). Thiol-ene "click" reactions and recent applications in polymer and materials synthesis. *Polymer Chemistry, 1*(1), 17.
Lowe, A. B. (2014). Thiol–ene "click" reactions and recent applications in polymer and materials synthesis: A first update. *Polymer Chemistry, 5*(17), 4820–4870.
Lu, D. R., Xiao, C. M., Xu, S. J., & Ye, Y. F. (2011). Tailor-made starch-based conjugates containing well-defined poly(vinyl acetate) and its derivative poly(vinyl alcohol). *Express Polymer Letters, 5*(6), 535–544.
Lu, D., Xiao, C., & Sun, F. (2012). Controlled grafting of poly(vinyl acetate) onto starch via RAFT polymerization. *Journal of Applied Polymer Science, 124*(4), 3450–3455.
Lyytikainen, J., Ovaska, S. S., Soboleva, E., Rinkunas, R., Lozovski, T., Maldzius, R., & Backfolk, K. (2018). Optimizing electric corona treatment for hydroxypropylated starch-based coatings. *Carbohydrate Polymers, 197*, 359–365.
Manoi, K., & Rizvi, S. S. H. (2010). Physicochemical characteristics of phosphorylated cross-linked starch produced by reactive supercritical fluid extrusion. *Carbohydrate Polymers, 81*(3), 687–694.
Mansfeld, U., Pietsch, C., Hoogenboom, R., Becer, C. R., & Schubert, U. S. (2010). Clickable initiators, monomers and polymers in controlled radical polymerizations – A prospective combination in polymer science. *Polymer Chemistry, 1*(10), 1560.
Masina, N., Choonara, Y. E., Kumar, P., du Toit, L. C., Govender, M., Indermun, S., ... Pillay, V. (2017). A review of the chemical modification techniques of starch. *Carbohydrate Polymers, 157*, 1226–1236.
Mateyawa, S., Xie, D. F., Truss, R. W., Halley, P. J., Nicholson, T. M., Shamshina, J. L., & McNally, T. (2013). Effect of the ionic liquid 1-ethyl-3-methylimidazolium acetate on the phase transition of starch: Dissolution or gelatinization? *Carbohydrate Polymers, 94*(1), 520–530.
Matyjaszewski, K. (2012). Atom transfer radical polymerization (ATRP): Current status and future perspectives. *Macromolecules, 45*(10), 4015–4039.
Mazzocchetti, L., Tsoufis, T., Rudolf, P., & Loos, K. (2014). Enzymatic synthesis of amylose brushes revisited: Details from X-ray photoelectron spectroscopy and spectroscopic ellipsometry. *Macromolecular Bioscience, 14*(2), 186–194.
Men, Y., Du, X., Shen, J., Wang, L., & Liu, Z. (2015). Preparation of corn starch-g-polystyrene copolymer in ionic liquid: 1-ethyl-3-methylimidazolium acetate. *Carbohydrate Polymers, 121*, 348–354.
Moreira, G., Fedeli, E., Ziarelli, F., Capitani, D., Mannina, L., Charles, L., & Lefay, C. (2015). Synthesis of polystyrene-grafted cellulose acetate copolymers via nitroxide-mediated polymerization. *Polymer Chemistry, 6*(29), 5244–5253.
Mota-Morales, J. D., Sánchez-Leija, R. J., Carranza, A., Pojman, J. A., del Monte, F., & Luna-Bárcenas, G. (2018). Free-radical polymerizations of and in deep eutectic solvents: Green synthesis of functional materials. *Progress in Polymer Science, 78*, 139–153.
Muljana, H., Picchioni, F., Heeres, H. J., & Janssen, L. P. B. M. (2009). Supercritical carbon dioxide ($scCO_2$) induced gelatinization of potato starch. *Carbohydrate Polymers, 78*(3), 511–519.
Muljana, H., van der Knoop, S., Keijzer, D., Picchioni, F., Janssen, L. P. B. M., & Heeres, H. J. (2010). Synthesis of fatty acid starch esters in supercritical carbon dioxide. *Carbohydrate Polymers, 82*(2), 346–354.
Muljana, H., Picchioni, F., Knez, Z., Heeres, H. J., & Janssen, L. P. B. M. (2011). Insights in starch acetylation in sub- and supercritical CO_2. *Carbohydrate Research, 346*(10), 1224–1231.
Najafi Moghaddam, P., Fareghi, A. R., Entezami, A. A., & Ghaffari Mehr, M. A. (2013). Synthesis of biodegradable thermoplastic copolymers based on starch by atom

transfer radical polymerization (ATRP): Monolayer chain growth on starch. *Starch/Stärke, 65*(3–4), 210–218.
Nakamatsu, J., Torres, F. G., Troncoso, O. P., Min-Lin, Y., & Boccaccini, A. R. (2006). Processing and characterization of porous structures from chitosan and starch for tissue engineering scaffolds. *Biomacromolecules, 7*(12), 3345–3355.
Nie, Y., Tian, X., Liu, Y., Wu, K., & Wang, J. (2013). Research on starch-g-polyvinyl acetate and epoxy resin-modified corn starch adhesive. *Polymer Composites, 34*(1), 77–87.
Ohdan, K., Fujii, K., Yanase, M., Takaha, T., & Kuriki, T. (2006). Enzymatic synthesis of amylose. *Biocatalysis and Biotransformation, 24*(1–2), 77–81.
Omagari, Y., Kaneko, Y., & Kadokawa, J.-i. (2010). Chemoenzymatic synthesis of amylose-grafted alginate and its formation of enzymatic disintegratable beads. *Carbohydrate Polymers, 82*(2), 394–400.
Orio, S., Yamamoto, K., & Kadokawa, J.-i. (2017). Preparation and material application of amylose-polymer inclusion complexes by enzymatic polymerization approach. *Polymers, 9*(12), 729.
Orzolek, B. J., Rahman, M. A., & Iovine, P. M. (2018). Synthesis of biorenewable starch–Farnesene amphiphilic conjugates via transesterification of terpene-derived diels–Alder adducts. *ACS Sustainable Chemistry & Engineering, 6*(10), 13562–13569.
Paradkar, V. M., & Dordick, J. S. (1994). Aqueous-like activity of α-chymotrypsin dissolved in nearly anhydrous organic solvents. *Journal of the American Chemical Society, 116*(11), 5009–5010.
Patel, S., Venditti, R. A., Pawlak, J. J., Ayoub, A., & Rizvi, S. S. H. (2009). Development of cross-linked starch microcellular foam by solvent exchange and reactive supercritical fluid extrusion. *Journal of Applied Polymer Science, 111*(6), 2917–2929.
Petzold, K., Einfeldt, L., Günther, W., Stein, A., & Klemm, D. (2001). Regioselective functionalization of starch: Synthesis and ^{1}H NMR characterization of 6-*O*-Silyl ethers. *Biomacromolecules, 2*(3), 965–969.
Petzold, K., Klemm, D., Stein, A., & Günther, W. (2002). Synthesis and NMR characterization of regiocontrolled starch alkyl ethers. *Designed Monomers & Polymers, 5*(4) 451–426.
Petzold, K., Koschella, A., Klemm, D., & Heublein, B. (2003). Silylation of cellulose and starch-selectivity, structure analysis and subsequent reactions. *Cellulose, 10*, 251–269.
Qi, P., You, C., & Zhang, Y. H. P. (2014). One-pot enzymatic conversion of sucrose to synthetic amylose by using enzyme cascades. *ACS Catalysis, 4*(5), 1311–1317.
Ratcharak, O., & Sane, A. (2014). Surface coating with poly(trifluoroethyl methacrylate) through rapid expansion of supercritical CO2 solutions. *The Journal of Supercritical Fluids, 89*, 106–112.
Roesser, D. S., McCarthy, S. P., Gross, R. A., & Kaplan, D. L. (1996). Effects of substitution site on acetyl amylose biodegradability by amylase enzymes. *Macromolecules, 29*(1), 1–9.
Saikia, C., Das, M. K., Ramteke, A., & Maji, T. K. (2017). Evaluation of folic acid tagged aminated starch/ZnO coated iron oxide nanoparticles as targeted curcumin delivery system. *Carbohydrate Polymers, 157*, 391–399.
Sakamoto, M., Tseng, H., & Furuhata, K.-i. (1994). Regioselective chlorination of chitin with N-chlorosuccinimide-triphenylphosphine under homogeneous conditions in lithium chloride-N, N-dimethylacetamide. *Carbohydrate Research, 265*(2), 271–280.
Salimi, K., Yilmaz, M., Rzayev, Z. M., & Piskin, E. (2014). Controlled graft copolymerization of lactic acid onto starch in a supercritical carbon dioxide medium. *Carbohydrate Polymers, 114*, 149–156.
Sankri, A., Arhaliass, A., Dez, I., Gaumont, A. C., Grohens, Y., Lourdin, D., & Leroy, E. (2010). Thermoplastic starch plasticized by an ionic liquid. *Carbohydrate Polymers, 82*(2), 256–263.
Sciarini, L. S., Rolland-Sabaté, A., Guilois, S., Decaen, P., Leroy, E., & Le Bail, P. (2015). Understanding the destructuration of starch in water–ionic liquid mixtures. *Green Chemistry, 17*, 291–299.
Semsarilar, M., & Perrier, S. (2010). 'Green' reversible addition-fragmentation chain-transfer (RAFT) polymerization. *Nature Chemistry, 2*(10), 811–820.
Shey, J., Holtman, K. M., Wong, R. Y., Gregorski, K. S., Klamczynski, A. P., Orts, W. J., ... Imam, S. H. (2006). The azidation of starch. *Carbohydrate Polymers, 65*(4), 529–534.
Smith, E. L., Abbott, A. P., & Ryder, K. S. (2014). Deep eutectic solvents (DESs) and their applications. *Chemical Reviews, 114*(21), 11060–11082.
Song, H., Zhang, S.-F., Ma, X.-C., Wang, D.-Z., & Yang, J.-Z. (2007). Synthesis and application of starch-graft-poly(AM-co-AMPS) by using a complex initiation system of CS-APS. *Carbohydrate Polymers, 69*(1), 189–195.
Su, Q., Wang, Y., Zhao, X., Wang, H., Wang, Z., Wang, N., ... Zhang, H. (2020). Functionalized nano-starch prepared by surface-initiated atom transfer radical polymerization and quaternization. *Carbohydrate Polymers, 229*, 115390.
Tan, W., Li, Q., Wang, H., Liu, Y., Zhang, J., Dong, F., ... Guo, Z. (2016). Synthesis, characterization, and antibacterial property of novel starch derivatives with 1, 2, 3-triazole. *Carbohydrate Polymers, 142*, 1–7.
Tan, W., Li, Q., Dong, F., Qiu, S., Zhang, J., & Guo, Z. (2017). Novel 1,2,3-triazolium-functionalized starch derivatives: Synthesis, characterization, and evaluation of antifungal property. *Carbohydrate Polymers, 160*, 163–171.
Tan, W., Li, Q., Gao, Z., Qiu, S., Dong, F., & Guo, Z. (2017). Design, synthesis of novel starch derivative bearing 1,2,3-triazolium and pyridinium and evaluation of its antifungal activity. *Carbohydrate Polymers, 157*, 236–243.
Tanadul, O. U., VanderGheynst, J. S., Beckles, D. M., Powell, A. L., & Labavitch, J. M. (2014). The impact of elevated CO2 concentration on the quality of algal starch as a potential biofuel feedstock. *Biotechnology and Bioengineering, 111*(7), 1323–1331.
Tanaka, T., Gotanda, R., Tsutsui, A., Sasayama, S., Yamamoto, K., Kimura, Y., ... Kadokawa, J.-i. (2015). Synthesis and gel formation of hyperbranched supramolecular polymer by vine-twining polymerization using branched primer–guest conjugate. *Polymer, 73*, 9–16.
Tasdelen, M. A. (2011). Diels–Alder "click" reactions: Recent applications in polymer and material science. *Polymer Chemistry, 2*(10), 2133.
Tavares, A. P., Rodríguez, O., & Macedo, E. A. (2013). *New generations of ionic liquids applied to enzymatic biocatalysis*.
Tommasi, E., Cravotto, G., Galletti, P., Grillo, G., Mazzotti, M., Sacchetti, G., & Tagliavini, E. (2017). Enhanced and selective lipid extraction from the microalga P. Tricornutum by dimethyl carbonate and supercritical CO2 using deep eutectic solvents and microwaves as pretreatment. *ACS Sustainable Chemistry & Engineering, 5*(9), 8316–8322.
Ubeyitogullari, A., & Ciftci, O. N. (2016). Formation of nanoporous aerogels from wheat starch. *Carbohydrate Polymers, 147*, 125–132.
Uliniuc, A., Popa, M., Drockenmuller, E., Boisson, F., Leonard, D., & Hamaide, T. (2013). Toward tunable amphiphilic copolymers via CuAAC click chemistry of oligocaprolactones onto starch backbone. *Carbohydrate Polymers, 96*(1), 259–269.
van der Maarel, M. J. E. C., & Leemhuis, H. (2013). Starch modification with microbial alpha-glucanotransferase enzymes. *Carbohydrate Polymers, 93*(1), 116–121.
van der Vlist, J., Schonen, I., & Loos, K. (2011). Utilization of glycosyltransferases for the synthesis of a densely packed hyperbranched polysaccharide brush coating as artificial glycocalyx. *Biomacromolecules, 12*(10), 3728–3732.
Vanier, N. L., El Halal, S. L. M., Dias, A. R. G., & da Rosa Zavareze, E. (2017). Molecular structure, functionality and applications of oxidized starches: A review. *Food Chemistry, 221*, 1546–1559.
Varona, S., Rodríguez-Rojo, S., Martín, Á., Cocero, M. J., & Duarte, C. M. M. (2011). Supercritical impregnation of lavandin (Lavandula hybrida) essential oil in modified starch. *The Journal of Supercritical Fluids, 58*(2), 313–319.
Vijayakrishna, K., Manojkumar, K., & Sivaramakrishna, A. (2015). *Ionic liquids as solvents and/or catalysts in polymerization. Applications of ionic liquids in polymer science and technology*. Springer355–387.
Villegas, M., Oliveira, A. L., Bazito, R. C., & Vidinha, P. (2019). Development of an integrated one-pot process for the production and impregnation of starch aerogels in supercritical carbon dioxide. *The Journal of Supercritical Fluids, 154*, 104592.
Waldmann, H., Gygax, D., Bednarski, M. D., Randall Shangraw, W., & Whitesides, G. M. (1986). The enzymic utilization of sucrose in the synthesis of amylose and derivatives of amylose, using phosphorylases. *Carbohydrate Research, 157*, c4–c7.
Wang, S., & Copeland, L. (2015). Effect of acid hydrolysis on starch structure and functionality: A review. *Critical Reviews in Food Science and Nutrition, 55*(8), 1081–1097.
Wang, J.-S., & Matyjaszewski, K. (1995). Controlled/" living" radical polymerization. Atom transfer radical polymerization in the presence of transition-metal complexes. *Journal of the American Chemical Society, 117*(20), 5614–5615.
Wang, Y., & Matyjaszewski, K. (2010). ATRP of MMA in polar solvents catalyzed by $FeBr_2$ without additional ligand. *Macromolecules, 43*(9), 4003–4005.
Wang, Y., & Xie, W. (2010). Synthesis of cationic starch with a high degree of substitution in an ionic liquid. *Carbohydrate Polymers, 80*(4), 1172–1177.
Wang, J., Yang, W., Wang, J., Wang, X., Wu, F., Yao, J., & Lei, Z. (2015). Regioselective sulfation of Artemisia sphaerocephala polysaccharide: Characterization of chemical structure. *Carbohydrate Polymers, 133*, 320–327.
Wang, L., Shen, J., Men, Y., Wu, Y., Peng, Q., Wang, X., & Liu, Z. (2015). Corn starch-based graft copolymers prepared via ATRP at the molecular level. *Polymer Chemistry, 6*(18), 3480–3488.
Wang, L., Qu, L., Wu, Y., Men, Y., & Liu, Z. (2017). Synthesis of regioselective starch-based macroinitiators at molecular level. *Starch - Stärke, 69*(11–12), 1700043.
Whistler, R. L., & Hirase, S. (1961). Introduction of 3, 6-anhydro rings into amylose and characterization of the products. *The Journal of Organic Chemistry, 26*(11), 4600–4605.
Wolfrom, M., & Wang, P. (1970). Amination of amylose at the C-2 position. *Carbohydrate Research, 12*(1), 109–114.
Wu, A. C., Witt, T., & Gilbert, R. G. (2013). Characterization methods for starch-based materials: State of the art and perspectives. *Australian Journal of Chemistry, 66*(12), 1550.
Wu, C., Yang, J., Xu, X., Gao, C., Lü, S., & Liu, M. (2016). Redox-responsive core-cross-linked mPEGylated starch micelles as nanocarriers for intracellular anticancer drug release. *European Polymer Journal, 83*, 230–243.
Xiao, C., Lu, D., Xu, S., & Huang, L. (2011). Tunable synthesis of starch-poly(vinyl acetate) bioconjugate. *Starch/Stärke, 63*(4), 209–216.
Xie, W., Shao, L., & Liu, Y. (2010). Synthesis of starch esters in ionic liquids. *Journal of Applied Polymer Science, 116*(1), 218–224.
Xie, W., Zhang, Y., & Liu, Y. (2011). Homogenous carboxymethylation of starch using 1-butyl-3-methylimidazolium chloride ionic liquid medium as a solvent. *Carbohydrate Polymers, 85*(4), 792–797.
Xie, F., Flanagan, B. M., Li, M., Sangwan, P., Truss, R. W., Halley, P. J., & McNally, T. (2014). Characteristics of starch-based films plasticised by glycerol and by the ionic liquid 1-ethyl-3-methylimidazolium acetate: A comparative study. *Carbohydrate Polymers, 111*, 841–848.
Xu, Q., Wang, Q., & Liu, L. (2008). Ring-opening graft polymerization ofL-lactide onto starch granules in an ionic liquid. *Journal of Applied Polymer Science, 107*(4), 2704–2713.
Yang, J., Gao, C., Lu, S., Zhang, X., Yu, C., & Liu, M. (2014). Physicochemical characterization of amphiphilic nanoparticles based on the novel starch-deoxycholic acid conjugates and self-aggregates. *Carbohydrate Polymers, 102*, 838–845.
Yang, X., Liu, W., Xi, G., Wang, M., Liang, B., Shi, Y., & Shi, C. (2019). Fabricating antimicrobial peptide-immobilized starch sponges for hemorrhage control and antibacterial treatment. *Carbohydrate Polymers*115012.
Zaidul, I. S. M., Noda, T., Sharif, K. M., Karim, A. A., & Smith, R. L. (2014). Reduction of gelatinization temperatures of starch blend suspensions with supercritical CO_2 treatment. *The Journal of Supercritical Fluids, 95*, 499–505.
Zarski, A., Ptak, S., Siemion, P., & Kapusniak, J. (2016). Esterification of potato starch by a biocatalysed reaction in an ionic liquid. *Carbohydrate Polymers, 137*, 657–663.
Zdanowicz, M. (2020). Starch treatment with deep eutectic solvents, ionic liquids and glycerol. A comparative study. *Carbohydrate Polymers*115574.

Zdanowicz, M., Spychaj, T., & Maka, H. (2016). Imidazole-based deep eutectic solvents for starch dissolution and plasticization. *Carbohydrate Polymers, 140*, 416–423.
Zdanowicz, M., Wilpiszewska, K., & Spychaj, T. (2018). Deep eutectic solvents for polysaccharides processing. A review. *Carbohydrate Polymers, 200*, 361–380.
Zhang, K., Wang, Z., Li, Y., Jiang, Z., Hu, Q., Liu, M., ... Zhao, Q. (2013). Dual stimuli-responsive N-phthaloylchitosan-graft-(poly(N-isopropylacrylamide)-block-poly(acrylic acid)) copolymer prepared via RAFT polymerization. *Carbohydrate Polymers, 92*(1), 662–667.
Zhang, Q., Wilson, P., Li, Z., McHale, R., Godfrey, J., Anastasaki, A., & Haddleton, D. M. (2013). Aqueous copper-mediated living polymerization: Exploiting rapid disproportionation of CuBr with Me6TREN. *Journal of the American Chemical Society, 135*(19), 7355–7363.
Zhang, Z., Shan, H., Chen, L., He, C., Zhuang, X., & Chen, X. (2013). Synthesis of pH-responsive starch nanoparticles grafted poly (l-glutamic acid) for insulin controlled release. *European Polymer Journal, 49*(8), 2082–2091.
Zhang, R., Zheng, X., Kuang, J., & Edgar, K. J. (2014). Glycan ester deacylation by TBAOH or TBAF: Regioselectivity vs. polysaccharide structure. *Carbohydrate Polymers, 113*, 159–165.
Zhang, B., Xie, F., Zhang, T., Chen, L., Li, X., Truss, R. W., & Rogers, R. D. (2016). Different characteristic effects of ageing on starch-based films plasticised by 1-ethyl-3-methylimidazolium acetate and by glycerol. *Carbohydrate Polymers, 146*, 67–79.
Zhang, B., Xie, F., Shamshina, J. L., Rogers, R. D., McNally, T., Halley, P. J., & Zhao, S. (2017). Dissolution of starch with aqueous ionic liquid under ambient conditions. *ACS Sustainable Chemistry & Engineering, 5*(5), 3737–3741.
Zhang, B., Xie, F., Shamshina, J. L., Rogers, R. D., McNally, T., Wang, D. K., & Chen, L. (2017). Facile preparation of starch-based electroconductive films with ionic liquid. *ACS Sustainable Chemistry & Engineering, 5*(6), 5457–5467.
Zhang, Q., & Zhu, S. (2015). Ionic liquids: Versatile media for preparation of vesicles from polymerization-induced self-assembly. *ACS Macro Letters, 4*(7), 755–758.
Zhao, X. F., Peng, L. Q., Wang, H. L., Wang, Y. B., & Zhang, H. (2018). Environment-friendly urea-oxidized starch adhesive with zero formaldehyde-emission. *Carbohydrate Polymers, 181*, 1112–1118.